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PHYSICS OF TECHNOLOGY

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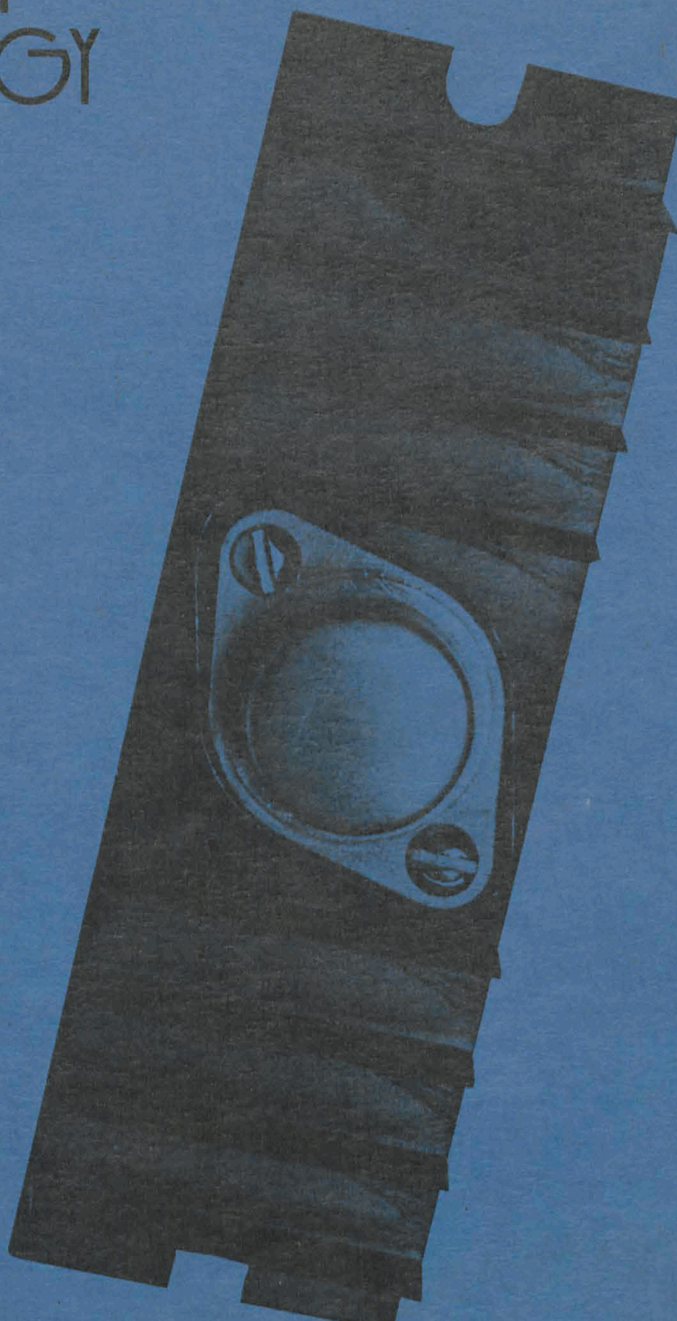

THE POWER TRANSISTOR

Temperature and Heat Transfer

THE POWER TRANSISTOR

A Module on Temperature and Heat Transfer

TERC

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In the early days of the Tech Physics Project A. A. Strassenburg, then Director of the AIP Office of Education, coordinated the module quality-control and advisory functions of the National Steering Committee. In 1972 Philip DiLavore became Project Coordinator and also assumed the responsibilities of editing and producing the final page copy for the modules.

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The Power Transistor

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Preface

ABOUT THIS MODULE

Its Purpose

The purpose of the Physics of Technology program is to give you an insight into some of the physical principles that are the basis of technology. To do this you are asked to study various technological devices. These devices have been chosen because their operation depends on some important physics principles. In this module the device is the power transistor. The methods used to keep it at a safe operating temperature are determined by examining the processes of heat transfer.

The PoT program has adopted a modular format with each module focusing on a single device. Thus you can select those modules that relate to your own interests or areas of specialty. This preface highlights some of the features of the modular approach so that you may use it efficiently and effectively.

Its Design

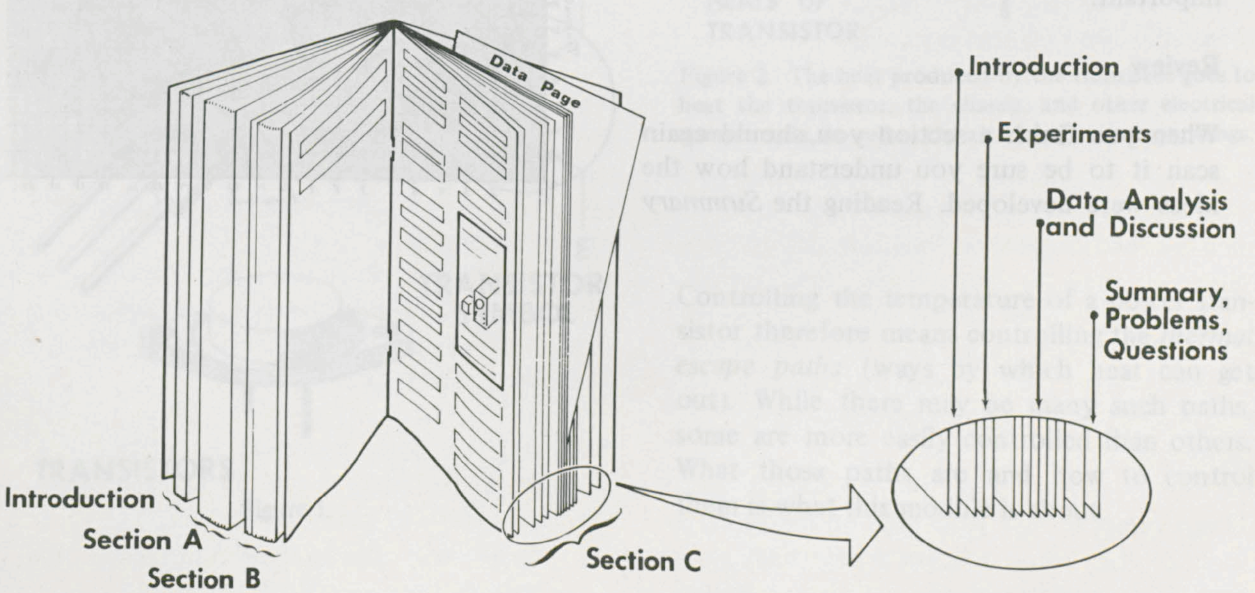
The module design is illustrated below. The *Introduction* explains why we have selected the power transistor to study and what physical principles will be illustrated in its behavior. Learning *Goals* are given, as well as *Prerequisite* skills and knowledge you should have before beginning. The three *Sections* of the module treat different aspects of the device. They are of increasing difficulty but each can be completed in about one week.

Each section begins with a brief *Introduction* to the topics treated and how they relate to the behavior of the device. The *Experiments* follow and take about two to three hours. Tear-out *Data Pages* are provided to record your data. The body of the section then describes the method of *Data Analysis* including a *Discussion* of the physical principles which explain your results. A *Summary* ends the section with *Problems* and *Questions* you can do to test your understanding.

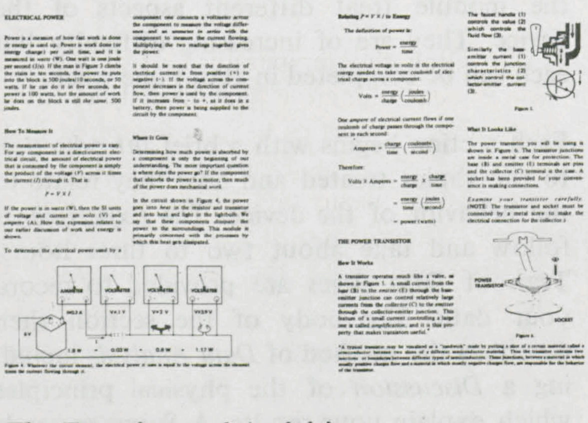
HOW TO USE THIS MODULE

To Begin

This module has been written so that it can be quickly and easily scanned. That is, you can get the gist of the ideas and experiments by



simply flipping from page to page, reading only the headings and italicized words, and looking at the illustrations. We suggest before you begin a section or an experiment that you scan through it in this way so that you will know where you are going.



ELECTRICAL POWER

Power is a measure of how fast work is done or energy is used up. Power is work done (or energy change) per unit time, and it is measured in watts (W). One watt is one joule per second (J/s). If the man in Figure 3 climbs the stairs in ten seconds, the power he puts into the block is 500 joules/10 seconds, or 50 watts. If he can do it in five seconds, the power is 100 watts, but the amount of work he does on the block is still *the same*, 500 joules.

How To Measure It

The measurement of electrical power is easy. For any component in a direct-current electrical circuit, the amount of electrical power that is consumed by the component is simply the product of the voltage (*V*) across it times the current (*I*) through it. That is:

$P = V \times I$

If the power is in watts (W), then the SI units of voltage and current are volts (V) and amperes (A). How this expression relates to our earlier discussion of work and energy is shown.

To determine the electrical power used by a component one connects a voltmeter across the component to measure the voltage difference and an ammeter in series with the component to measure the current flowing. Multiplying the two readings together gives the power.

It should be noted that the direction of electrical current is from positive (+) to negative (−). If the voltage across the component decreases in the direction of current flow, then power is used by the component. If it increases from − to +, as it does in a battery, then power is being supplied to the circuit by the component.

Where It Goes

Determining how much power is absorbed by a component is only the beginning of our understanding. The more important question is where does the power go? If the component that absorbs the power is a motor, then much of the power does mechanical work.

In the circuit shown in Figure 4, the power goes into *heat* in the resistor and transistor and into heat and light in the lightbulb. We say that these components *dissipate* the power to the surroundings. This module is primarily concerned with the processes by which this heat gets dissipated.

Figure 4. Wherever the circuit element, the electrical power it uses is equal to the voltage across the element times the current flowing through it.

Relating $P = V \times I$ to Energy

The definition of power is:

$\text{Power} = \frac{\text{energy}}{\text{time}}$

The electrical voltage in volts is the electrical energy needed to take one coulomb of electrical charge across a component:

$\text{Volts} = \frac{\text{energy}}{\text{charge}} \left(\frac{\text{joules}}{\text{coulomb}}\right)$

One *ampere* of electrical current flows if one coulomb of charge passes through the component in each second:

$\text{Amperes} = \frac{\text{charge}}{\text{time}} \left(\frac{\text{coulombs}}{\text{second}}\right)$

Therefore:

$\text{Volts} \times \text{Amperes} = \frac{\text{energy}}{\text{charge}} \times \frac{\text{charge}}{\text{time}} = \frac{\text{energy}}{\text{time}} \left(\frac{\text{joules}}{\text{second}}\right) = \text{power (watts)}$

THE POWER TRANSISTOR

How It Works

A transistor operates much like a valve, as shown in Figure 1. A small current from the base (B) to the *emitter* (E) through the base-emitter junction can control relatively large currents from the *collector* (C) to the emitter through the collector-emitter junction. This feature of a small current controlling a large one is called *amplification*, and it is this property that makes transistors useful.*

The faucet handle (1) controls the value (2) which controls the fluid flow (3).

Similarly the base-emitter current (1) controls the junction characteristics (2) which control the collector-emitter current (3).

Figure 1.

What It Looks Like

The power transistor you will be using is shown in Figure 6. The transistor junctions are inside a metal case for protection. The base (B) and emitter (E) terminals are pins and the collector (C) terminal is the case. A socket has been provided for your convenience in making connections.

Examine your transistor carefully. (NOTE: The transistor and socket must be connected by a metal screw to make the electrical connection for the collector.)

Figure 6.

*A typical transistor may be visualized as a "sandwich" made by putting a slice of a certain material called a semiconductor between two slices of a different semiconductor material. Thus the transistor contains two junctions or boundaries between different types of semiconductors. These junctions, between a material in which mostly positive charges flow and a material in which mostly negative charges flow, are responsible for the behavior of the transistor.

The Experimental Activities

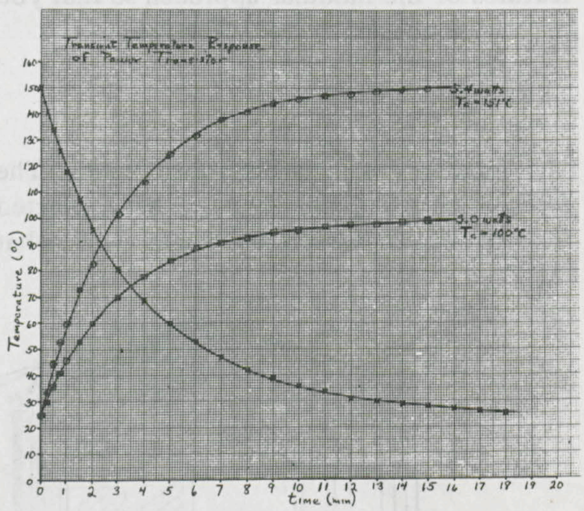
The heart of the Physics of Technology modules is the experimental study of various devices. Such study often involves learning to use a new measuring device or instrument. Since your observations and data usually will be analyzed *after* you leave the laboratory, it is important that you do the experiments carefully and take accurate data. A scan of the Data Analysis and Discussion *before* you begin the experiment will help you to know what aspects of the experiment and data are important.

Review

When you finish a section you should again scan it to be sure you understand how the ideas were developed. Reading the *Summary* will also help. Then you should try to answer the *Problems* and *Questions* to test your understanding and to be sure that you have achieved the *Goals* for that section. When you have completed the module, you may want to tear out certain pages for future reference; for example, conversion tables and methods of calibrating instruments.

The Data Analysis

The data you take will often have to be graphed to make it easier to understand. Graphing and graphical analysis are essential parts of experimental science. Understanding graphs is important for technology since technical information is often presented graphically. For these reasons, and since the discussion of your results will be based on your graphs, it is important that you prepare them clearly and accurately.



THE POWER TRANSISTOR

INTRODUCTION Why Study Power Transistors?

Transistor Performance Depends on Temperature

Transistors are basic components of modern electronic circuits. They come in many sizes and shapes and are designed for many circuit functions. *Power transistors* are heavy-duty transistors designed for applications in which large currents must be controlled. For example, they are used in hi-fi amplifiers.

The performance of a transistor, as well as of other circuit elements, depends to some extent on its temperature. As long as the temperature stays within a reasonable range, a transistor will perform properly. If it gets too hot, however, its behavior may change drastically, thus affecting the performance of the whole electronic circuit. When this happens, so-called "thermal runaway" can easily result, in which a transistor burns itself up. Controlling the temperature of electronic components is thus an important consideration in electronic design.

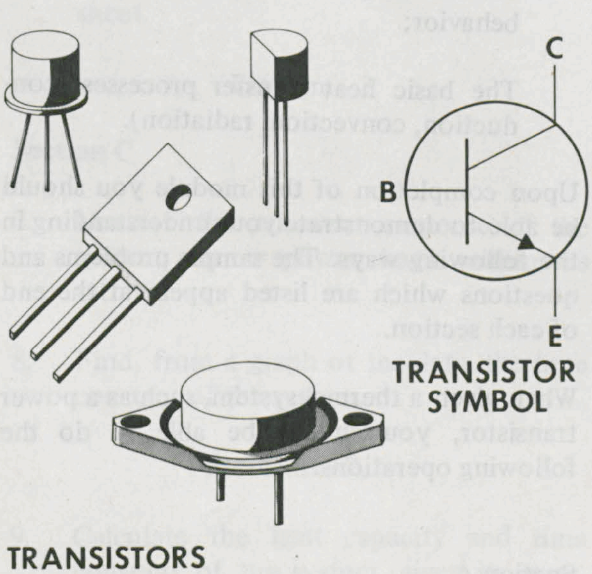


Figure 1.

Temperature Control Depends on Controlling Heat Flow

Controlling the temperature of a device involves controlling the heat that flows into or out of it. If a lot of heat is generated in the device, as it is in a power transistor, there must be a means by which this heat can escape. The portion of the heat that does not get out will raise the temperature of the device.

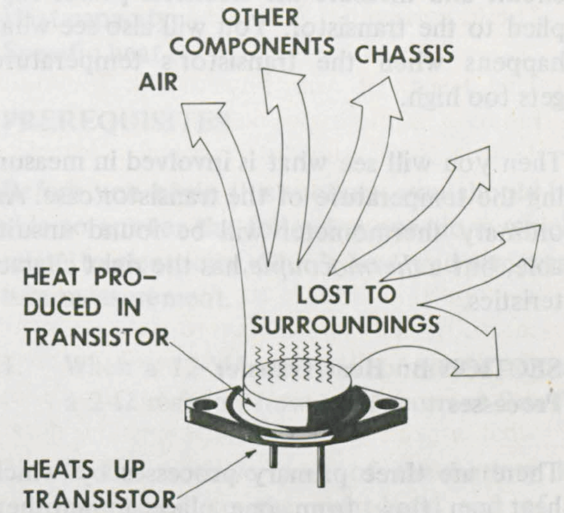


Figure 2. The heat produced by the transistor goes to heat the transistor, the chassis, and other electrical components, as well as the air and other surroundings.

Controlling the temperature of a power transistor therefore means controlling the *thermal escape paths* (ways by which heat can get out). While there may be many such paths, some are more easily controlled than others. What those paths are and how to control them is what this module is about.

WHAT WILL YOU LEARN?

SECTION A: Measuring Electrical Power and Temperature

We have chosen the power transistor for study for several reasons. For one thing, its temperature is important for its proper operation. Also, the power fed into the transistor can be easily varied. Finally, temperature control of power transistors will illustrate most of the important principles of the physics of heat transfer.

In the first experiment you will explore some properties of a common power transistor. You will set up a typical power transistor circuit and measure the electrical power supplied to the transistor. You will also see what happens when the transistor's temperature gets too high.

Then you will see what is involved in measuring the temperature of the transistor case. An ordinary thermometer will be found unsuitable, but a *thermocouple* has the right characteristics.

SECTION B: Heat Transfer Processes

There are three primary processes by which heat can flow from one place to another. They are *conduction, convection,* and *radiation.* Each of these processes carries some heat away from the power transistor, but with different efficiencies. In the experiments of this section you will explore these processes and see what heat sinks and fans are, and how they are used to increase the heat transfer efficiency.

SECTION C: Transient Thermal Behavior

When things change from one temperature to another, they often do so in a way that can be described mathematically. These changing conditions are called *transients* and they happen in a relatively short time.

With the skills you learn in the first experiment you will be able to measure the transient temperature change of the power transistor when it is suddenly switched on or off. You will see that the temperature follows a pattern common to many other transient phenomena. You will learn how to describe these changes using such terms as *time constant, thermal resistance,* and *heat capacity.*

GOALS

The general goal of this module is to give you an understanding of the principles of heat transfer, and of how these principles apply to practical devices, such as a power transistor.

This involves a knowledge of:

How to measure temperature and power;

The basic quantities used to describe a thermal system (heat capacity, thermal resistance);

The meaning and description of transient behavior;

The basic heat transfer processes (conduction, convection, radiation).

Upon completion of this module you should be able to demonstrate your understanding in the following ways. The sample problems and questions which are listed appear at the end of each section.

When given a thermal system, such as a power transistor, you should be able to do the following operations.

Section A

1. Determine the power ratings of the system from specification sheets.

Problems - 2, 3, 5

2. Properly use a thermocouple for measuring the temperature of the system.

Problems - 4, 5
Questions - 1, 2, 3, 4

Section B

3. Measure the transistor's final equilibrium temperature for various power levels within its ratings and find the thermal resistance.

4. Identify the primary heat transfer processes and the factors which affect the thermal resistance for each process.

Problems - 1, 3
Questions - 2, 3

5. Lower the thermal resistance of the system to improve the power dissipation.

Question - 1

6. Find a good operating point for the system, using the thermal resistance, the final temperature, and a specification sheet.

Problem - 2

Section C

7. Measure the transient response of the system for a power level within its ratings.

8. Find, from a graph of the data, the time constant of the system.

Problems - 2, 5

9. Calculate the heat capacity and time constant of the system, given its mass, the material of which it is made and the thermal resistance.

Problem - 1

10. Estimate the final temperature, time constant, and thermal resistance of the system, given appropriate data.

Problem - 3

You should also be able to explain the meaning of the following terms.

In Section B

Conduction (thermal conductivity)
Convection
Radiation

In Section C

Time constant
Thermal resistance
Heat capacity
Specific heat

PREREQUISITES

Before you begin this module, you should be able to answer the following questions which relate to electricity, Ohm's Law, and temperature measurement.

1. When a 12-V battery is connected across a 2-Ω resistor, how much current flows?

2. If the positive post of the battery is connected to the right-hand end of a resistor and the negative side to the left-hand end, in which direction does current flow in the resistor?

3. If a 3-V flashlight lamp draws a current of 2 A, how much power does it use?

4. A 12-V automobile battery is capable of delivering 1200 W of power for a short period of time. What current will it produce?

5. A 6-V battery is connected with two resistors, one of 4 Ω and one of 8 Ω, which are in series.

   a. What is the current in the circuit?

b. What is the voltage (potential difference) across each of the resistors?

6. What are the boiling point and freezing points of water on the Celsius temperature scale?

Answers

1. 6 A
2. Right to left
3. 6 W
4. 100 A
5. 0.5 A, 2 V and 4 V
6. 100°C and 0°C

SECTION A

Measuring Electrical Power and Temperature

INTRODUCTION

The terms *temperature* and *power* are used frequently in discussions of heat transfer. Since they are such key quantities, most of this section will deal with what they are and how they are measured. It will also be important to know how the power transistor operates and how it is affected by changes in power and temperature. Most of this information is given by the manufacturer on a "specification sheet" (see the example on page 19). By the end of this module you should be quite familiar with all of the "Thermal Characteristics" it describes.

What Is Energy?. . .Work?

These are questions which should be answered precisely, but it is not always easy to do so. In everyday speech, someone who never seems to need a rest is said to have "lots of *energy.*" Someone who carries heavy boxes upstairs will feel tired; he has used a large amount of energy doing *work.* People who can do physical labor faster than others are called "more *powerful.*"

Our understanding of work, energy and power can be made more precise by using exact mathematical definitions. For instance, although you may get tired holding up a heavy object or even walking at a steady pace across the room with it, you are not doing any work.

In the precise sense, work is done only when you exert a force on an object and thereby cause it to move *in the direction* of the line along which you are pushing or pulling. For example, if you lift the heavy object up you *are* doing work, because the direction of the force and the direction of the motion are both up. (If the motion is neither along the line of the force nor perpendicular to it, part of the force does work and part of it does not.) In the figure, the man raising the block does work, the amount of which depends only on how high he climbs.

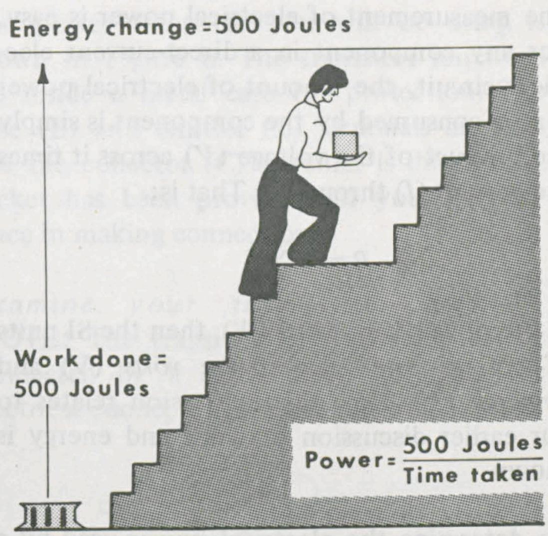


Figure 3.

Energy comes in many forms but, in general, it can be used up to do work. Since energy and work are so closely related, they are both measured in the same units. In the standard International System of Units ("SI units"), energy and work are measured in *joules* (J). "SI" really stands for *Systeme International,* since French is the international language. In this module, we shall be concerned with electrical energy and thermal (heat) energy.

ELECTRICAL POWER

Power is a measure of how fast work is done or energy is used up. Power is work done (or energy change) per unit time, and it is measured in *watts* (W). One watt is one joule per second (J/s). If the man in Figure 3 climbs the stairs in ten seconds, the power he puts into the block is 500 joules/10 seconds, or 50 watts. If he can do it in five seconds, the power is 100 watts, but the amount of work he does on the block is still *the same,* 500 joules.

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To determine the electrical power used by a component one connects a voltmeter *across* the component to measure the voltage difference and an ammeter *in series* with the component to measure the current flowing. Multiplying the two readings together gives the power.

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Where It Goes

Determining how much power is absorbed by a component is only the beginning of our understanding. The more important question is where does the power go? If the component that absorbs the power is a motor, then much of the power does mechanical *work.*

In the circuit shown in Figure 4, the power goes into *heat* in the resistor and transistor and into heat and light in the lightbulb. We say that these components *dissipate* the power to the surroundings. This module is primarily concerned with the processes by which this heat gets dissipated.

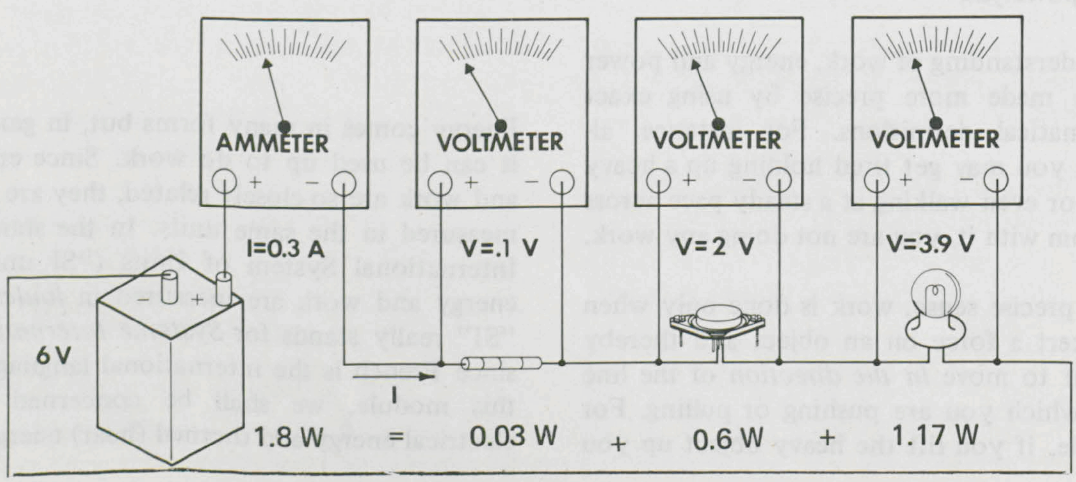


Figure 4. Whatever the circuit element, the electrical power it uses is equal to the voltage across the element times the current flowing through it.

Relating $P = V \times I$ to Energy

The definition of power is:

$$\text{Power} = \frac{\text{energy}}{\text{time}}$$

The electrical voltage in *volts* is the electrical energy needed to take one *coulomb* of electrical charge across a component:

$$\text{Volts} = \frac{\text{energy}}{\text{charge}}\left(\frac{\text{joules}}{\text{coulomb}}\right)$$

One *ampere* of electrical current flows if one coulomb of charge passes through the component in each second:

$$\text{Amperes} = \frac{\text{charge}}{\text{time}}\left(\frac{\text{coulombs}}{\text{second}}\right)$$

Therefore:

$$\text{Volts} \times \text{Amperes} = \frac{\text{energy}}{\text{charge}} \times \frac{\text{charge}}{\text{time}}$$

$$= \frac{\text{energy}}{\text{time}}\left(\frac{\text{joules}}{\text{second}}\right)$$

$$= \text{power (watts)}$$

THE POWER TRANSISTOR

How It Works

A transistor operates much like a valve, as shown in Figure 5. A small current from the *base* (B) to the *emitter* (E) through the base-emitter junction can control relatively large currents from the *collector* (C) to the *emitter* through the collector-emitter junction. This feature of a small current controlling a large one is called *amplification*, and it is this property that makes transistors useful.*

The faucet handle (1) controls the valve (2) which controls the fluid flow (3).

Similarly the base-emitter current (1) controls the junction characteristics (2) which control the collector-emitter current (3).

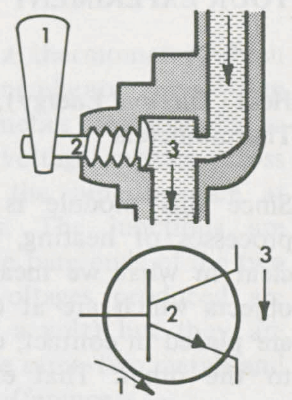


Figure 5.

What It Looks Like

The power transistor you will be using is shown in Figure 6. The transistor junctions are inside a metal case for protection. The base (B) and emitter (E) terminals are pins and the collector (C) terminal is the case. A socket has been provided for your convenience in making connections.

Examine your transistor carefully. (NOTE: The transistor and socket must be connected by a metal screw to make the electrical connection for the collector.)

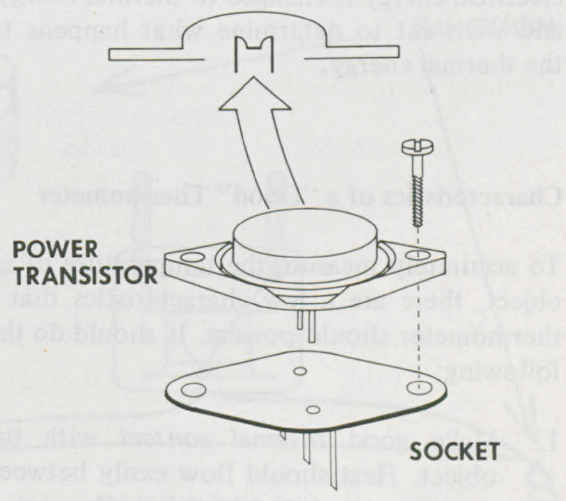


Figure 6.

*A typical transistor may be visualized as a "sandwich" made by putting a slice of a certain material called a *semiconductor* between two slices of a different semiconductor material. Thus the transistor contains two *junctions* or boundaries between different types of semiconductors. These junctions, between a material in which mostly positive charges flow and a material in which mostly negative charges flow, are responsible for the behavior of the transistor.

CHOOSING A THERMOMETER FOR YOUR EXPERIMENT

Heat (Thermal Energy), Temperature and Thermometers

Since this module is concerned with the processes of heating, it is important to be clear in what we mean by *heat.* When two objects which are at different temperatures are placed in contact, energy flows from one to the other. That energy transfer, which occurs only because the objects are at different temperatures, is *heat.* In the process, the cooler object warms up and the warmer one cools down, until they are at the same temperature. Then the heat transfer stops.

While this definition doesn't explain all we want to know about heat, it does indicate the general areas of concern. First, heat is closely related to temperature. To study heat, therefore, we must be able to accurately measure temperature. The second half of Section A is devoted to learning about *thermometers,* the instruments used to measure temperature.

Second, heat is a form of energy. We call this form *thermal energy* after the Greek word for heat, *therme.* In the power transistor the electrical energy is changed to thermal energy, and we want to determine what happens to the thermal energy.

Characteristics of a "Good" Thermometer

To accurately measure the temperature of an object, there are a few characteristics that a thermometer should possess. It should do the following:

1. Make good *thermal contact* with the object. Heat should flow easily between the object and the thermometer, so that they are at the same temperature.
2. Leave the *temperature* of the object *unchanged.* The amount of heat that flows to the thermometer should be small enough that the object's temperature doesn't change noticeably.
3. *Respond* reasonably *quickly* to changes in the object's temperature. If the temperature of the object changes, the temperature of the thermometer should change quickly in response.
4. Respond over the *range of temperatures* of the object. Further it should not be damaged by the highest and lowest temperatures of the object.
5. Be *accurately calibrated.* That is, it should have a scale which accurately reads the temperature, or which can be accurately related to temperature.
6. Have *adequate sensitivity.* That is, there should be measurable change in its reading with small temperature changes.

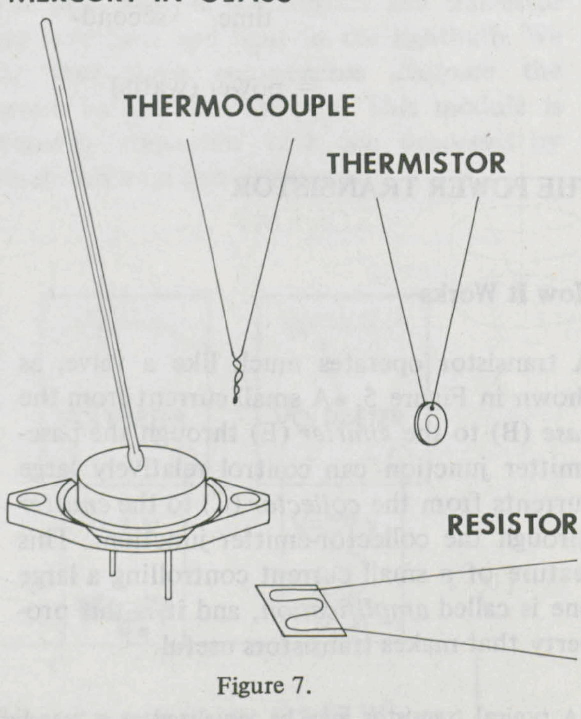


Figure 7.

How well does the ordinary mercury thermometer meet these criteria for measuring the temperature of the air, your body, and various objects? You will explore this in your experiments.

Some Thermometers to Choose From

Several types of thermometers are illustrated in Figure 7. Which do you recognize? Which do you think has the characteristics necessary to measure the temperature of the power transistor? Why?

You may find that more than one type of thermometer has the characteristics described which are needed for your measurement. If so, then your choice will depend on other less important features such as familiarity, availability, price and convenience.

The Thermocouple

The *thermocouple* is a thermometer which depends on an interesting phenomenon. When two wires of different metals are connected as shown in Figure 8, a voltage appears across the circuit whenever the junctions are at different temperatures. The junctions are made by connecting the bare ends of the two wires together. The voltages produced are small (thousandths of a volt) but they are always the same for the same two metals and the same temperature difference.

In Section A you will learn to use the thermocouple for measuring temperatures. Though we might have chosen one of the other types of thermometers, this one will best serve our purpose. You will see why it is better than a mercury-in-glass thermometer for measuring the transistor's temperature.

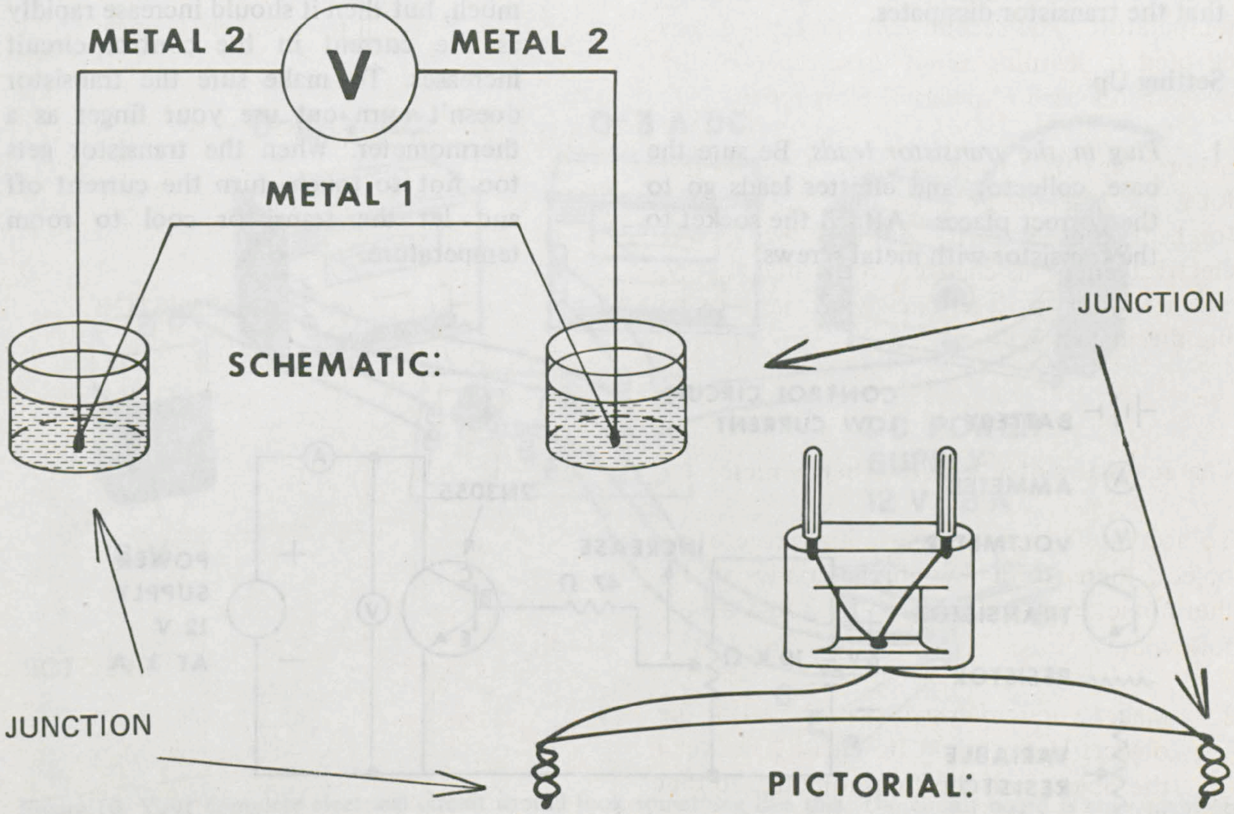


Figure 8.

EXPERIMENT A-1. Behavior of the Power Transistor

The purpose of this first experiment is to familiarize you with the behavior of the power transistor. You will set up an electrical circuit, consisting of two parts: a control section and an output section. A circuit diagram is shown in Figure 9 and a pictorial view is shown in Figure 10.

The control section uses a 6-V battery, a 10,000-Ω (10-kΩ) variable resistor, and a 47-Ω resistor which protects the circuit from high currents, and the base-emitter part of the transistor.

The output section uses a 12-V power supply and the collector-emitter part of the transistor. This part of the circuit would normally be connected to another transistor, a speaker or some other large-current device. In this experiment, however, it will be connected to meters which measure the electrical power that the transistor dissipates.

Setting Up

1. *Plug in the transistor leads.* Be sure the base, collector, and emitter leads go to the correct places. Attach the socket to the transistor with metal screws.

2. *Connect the meter, power supply and battery.* First, make sure that the power supply is off. Be certain that everything is attached with the correct polarity.

3. *Turn the variable resistor fully counterclockwise,* so that no current will flow in the output circuit when the power supply is turned on.

Testing the Circuit

4. *Turn on the power supply.* The voltmeter should read the power supply voltage, about 12 volts, but the ammeter should show no current flowing.

5. *Slowly turn the variable resistor clockwise.* At first the current won't increase much, but then it should increase rapidly as the current in the control circuit increases. To make sure the transistor doesn't burn out use your finger as a thermometer. When the transistor gets too hot to touch, turn the current off and let the transistor cool to room temperature.

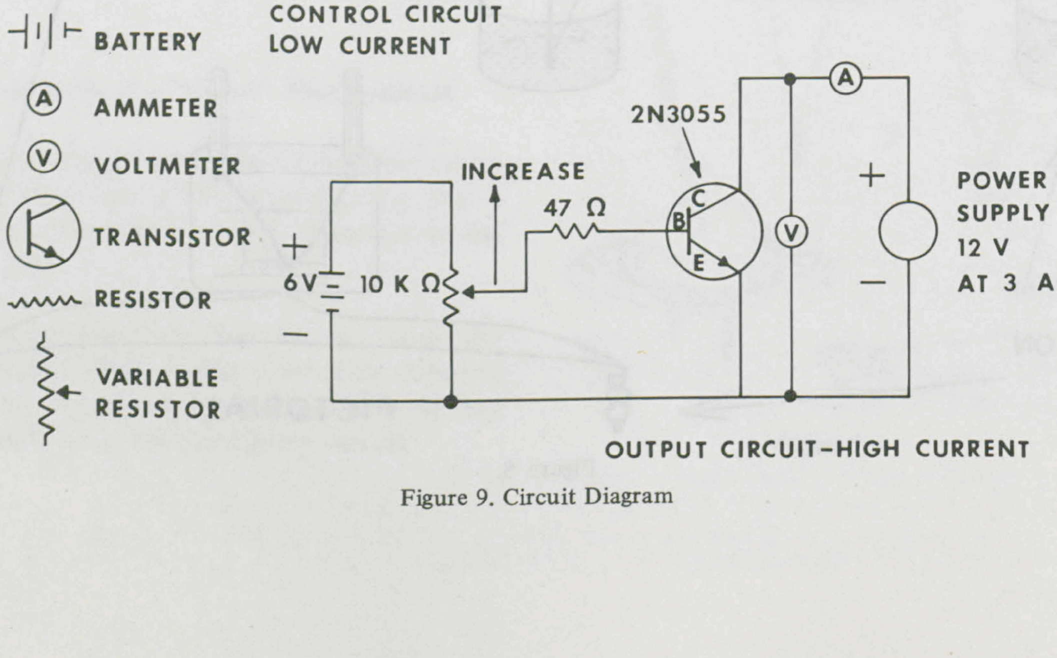


Figure 9. Circuit Diagram

Observing the Transistor Behavior

6. *Set the variable resistor so that 0.3 A flows in the output circuit.* Without changing the setting, watch the output current drift slowly upward as the transistor heats up.

7. *Record the current and voltage values* when the current stops changing. Is the transistor very hot?

   $V =$ $I =$

   Calculate the power being dissipated by the transistor:

   $P =$

8. *Turn down the variable resistor,* turn off the power supply, and disconnect the battery.

9. **Optional:** Place a separate milliammeter (0 - 5 mA) in the control circuit. Observe how the output current changes when the control current is changed. Calculate the *current gain* of the device by dividing the output current by the control current. Does this value change with transistor temperature? Compare your result with the values given on the sheet of transistor specifications which appears on page 19?

What Have You Observed?

This experiment shows that the transistor's characteristics, such as its ability to amplify current, depend on its temperature. In most applications it is necessary to have a constant output current for a given control current. Thus, the temperature must be kept fairly constant, even though the amount of power used may be quite large.

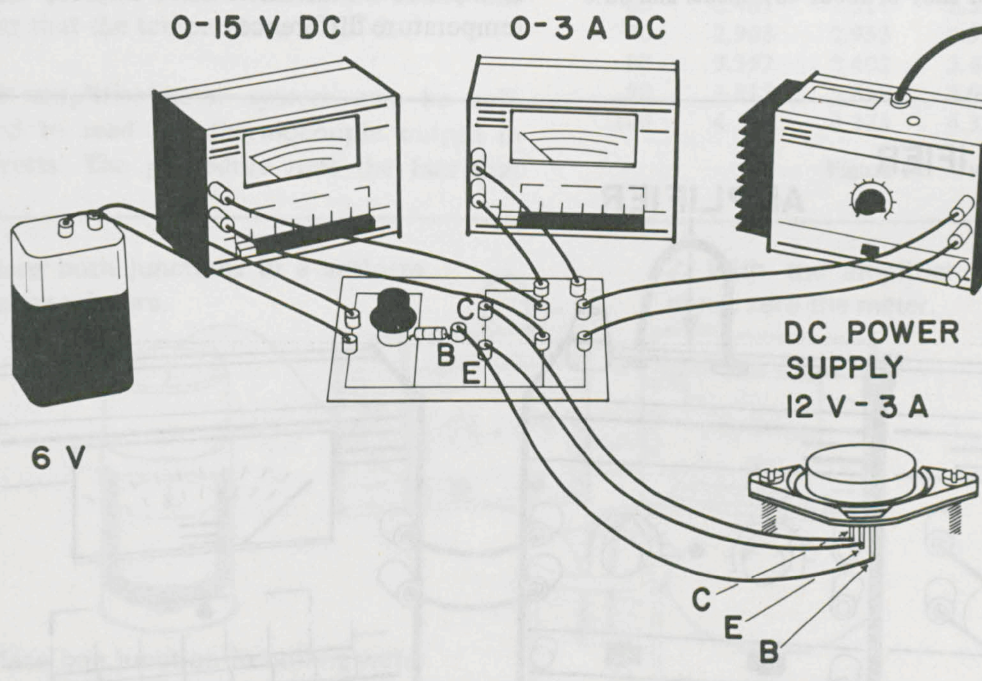


Figure 10. Your complete electrical circuit should look something like this. The circuit board is convenient but not necessary.

EXPERIMENT A-2. Use of the Thermocouple

The thermocouple you will be using is made from two wires, one of copper and one of constantan.* The two wires are welded together at each end to form the junctions. The copper wire is then cut and the cut ends are attached to a plug. The voltage that appears at the plug is developed between the two junctions.

The voltages in these experiments will be only a few millivolts. Since most meters require at least tenths of volts to move their needles, an *amplifier* is necessary. Follow the procedure shown to set up your temperature measuring system.

Procedure

1. *Assemble the system as shown below.* The thermocouple is plugged into the preamplifier which in turn is plugged into the amplifier. The meter is connected to the amplifier output by two jumper leads. Put the meter on the 0 to 2-V scale.

2. *Switch on the amplifier* and turn the *Gain* up to its fullest.

3. Adjust the amplifier *Zero* control until the meter reads zero. In order for this to be an accurate zero reading, the two junctions must be at exactly the same temperature. Figure out a way to be sure this is true.

4. *Explore temperature differences using the thermocouple.* Change the temperature of each junction and see what happens to the meter reading. Reduce the amplifier gain as necessary.

The thermocouple voltage should depend only on the *difference* in temperature between the two junctions. Place the junctions at two different temperatures and then reverse them while reversing the meter polarity. Is the above statement true? Explore various temperature differences.

*Constantan is an alloy of about 40% nickel and 60% copper.

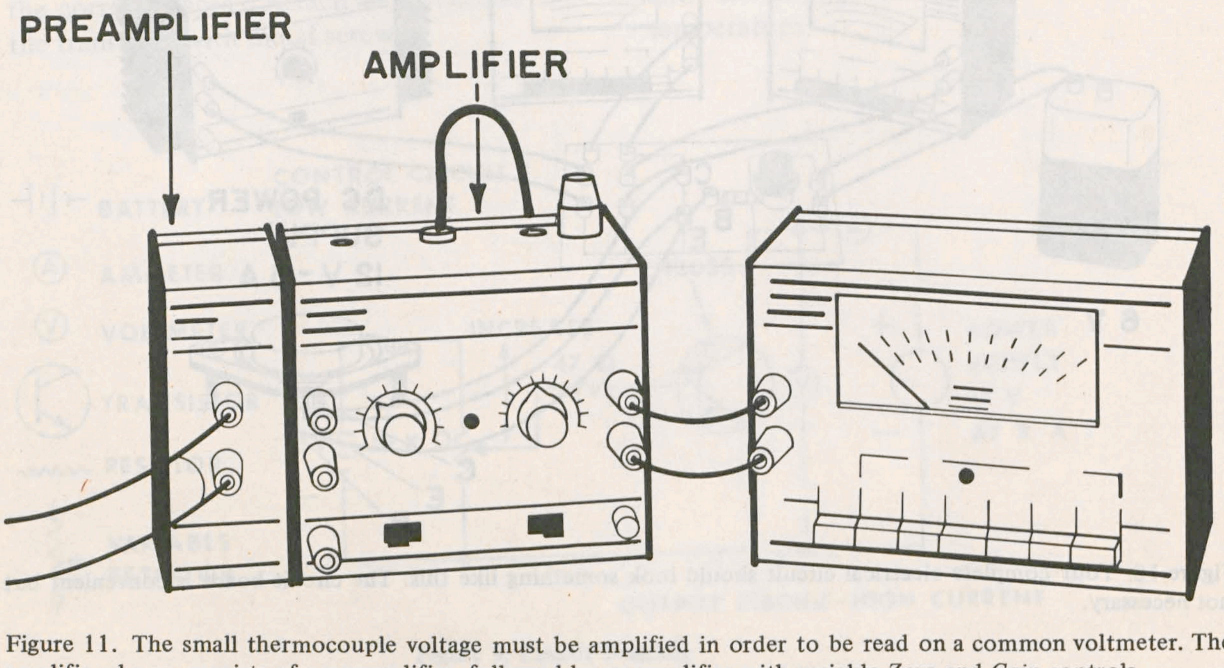


Figure 11. The small thermocouple voltage must be amplified in order to be read on a common voltmeter. The amplifier shown consists of a preamplifier, followed by an amplifier with variable *Zero* and *Gain* controls.

EXPERIMENT A-3. Calibrating the Thermocouple System

In thermocouples which are made of the same two materials, a given junction temperature difference always yields the same voltage. This property of thermocouples makes it possible to publish calibration tables of these voltages for various thermocouple materials. A calibration table for copper-constantan thermocouples appears at the back of this module.

In measurement, one junction, called the *reference junction,* is usually kept at a known, constant temperature, and the other one is attached to the object to be measured. The reference junction temperature is usually 0°C (melting point of ice), so the calibration tables often give only the temperature of the measuring junction and the voltage, assuming the reference junction to be at 0°C.

For example, suppose that a copper-constantan thermocouple voltage is measured to be 1.71 millivolts (mV). The nearest value in the table is 1.694 mV. As shown in the sample portion of the calibration table, this means that the temperature is 42°C.

Your amplifier/meter system can be calibrated to read the thermocouple output in millivolts. The procedure uses the fact that when the reference junction is at 0°C and the other junction is at 100°C (temperature of boiling water), the thermocouple voltage is 4.277 mV (see the table).

With the junctions at 0°C and 100°C, the amplifier gain is adjusted so that the meter reads 4.277 mV on a scale which goes from 0 to 10 mV. If the amplifier gain is constant, the meter will then read the thermocouple voltage, from 0 to 10 mV.

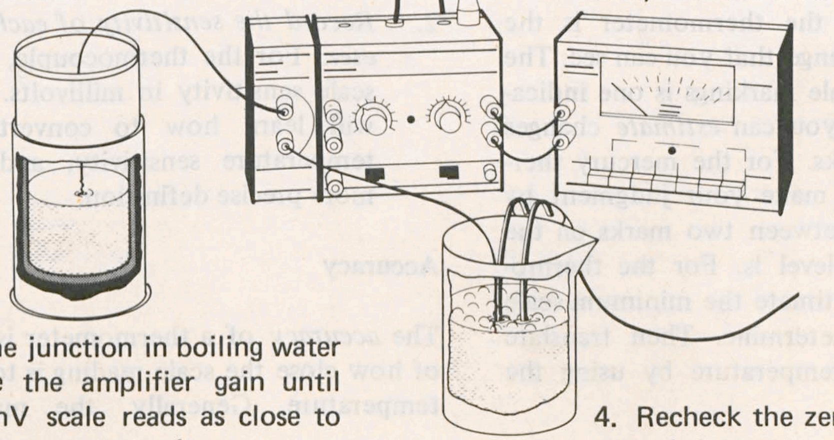
Temperature Difference	—	Thermocouple Voltage
42°C		1.71 mV

°C	0	1	2	3
(+)0	0.000	0.038	0.077	0.116
10	0.389	0.429	0.468	0.508
20	0.787	0.827	0.868	0.908
30	1.194	1.235	1.277	1.318
40	1.610	1.652	1.694	1.737
50	2.035	2.078	2.121	2.164
60	2.467	2.511	2.555	2.599
70	2.908	2.953	2.997	3.042
80	3.357	3.402	3.448	3.493
90	3.813	3.859	3.906	3.952
100	4.277	4.324	4.371	4.418

Figure 12.

1. Place both junctions in a uniform ice/water mixture.

2. With the amplifier gain at maximum, zero the meter.



3. Place one junction in boiling water and reduce the amplifier gain until the 0-10 mV scale reads as close to 4.277 mV as you can get it.

4. Recheck the zero and gain settings several times.

Figure 13.

EXPERIMENT A-4. Comparing the Thermocouple and the Mercury-in-Glass Thermometer

In the introduction we listed some of the characteristics that a "good" thermometer should have in order to make accurate temperature measurements. Take a moment to reread these characteristics and see if you understand what each means.

In the following experiments, you will have an opportunity to explore some of these characteristics for a mercury-in-glass thermometer and for a thermocouple. First you will explore their ranges, sensitivities, accuracies, and response times.

Then you will use each of them to measure the temperature of the transistor case, looking in particular at thermal contact and size effects. After these experiments you will be able to judge for yourself which is the better thermometer for your measurements.

Range and Sensitivity

The *range* of the thermometer is from the highest to the lowest temperature that it will measure. For the mercury thermometer, the range can be read directly from the highest and the lowest numbers on the glass scale. For the thermocouple it is determined by the limits on the meter scale. Since the meter reads millivolts, this must be converted into temperature by using the calibration table.

The *sensitivity* of the thermometer is the smallest reading change that you can see. The closeness of the scale markings is one indication but generally you can *estimate* changes between these marks. For the mercury thermometer you can make your judgment by estimating where between two marks on the glass the mercury level is. For the thermocouple you must estimate the minimum scale change you can determine. Then translate that reading into temperature by using the calibration table.

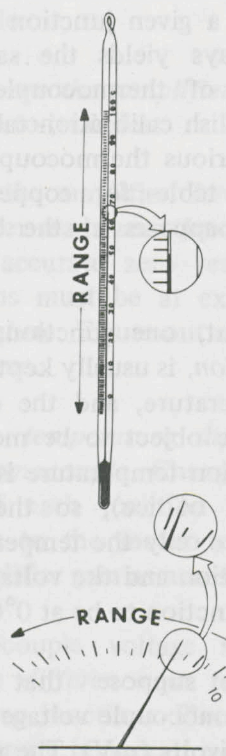


Figure 14.

1. *Record the range of each of your thermometers* on the data pages for this section which are at the back of the module. Assume the thermocouple range to be the same as the scale range, even though it is actually greater.

2. *Record the sensitivity of each thermometer.* For the thermocouple, record the scale sensitivity in millivolts. Later you will learn how to convert this into temperature sensitivity, and give it a more precise definition.

Accuracy

The *accuracy* of a thermometer is a measure of how close the scale reading is to the actual temperature. Generally, the manufacturer

indicates the accuracy by how close he makes the scale divisions. If they are every 1°C apart he claims that the true temperature is *at least* within 1°C of the scale reading, though it may be closer.

While it would be tedious to check the accuracy over the whole range, we can check it at a couple of temperatures. We may then assume that, if these are correct, the rest of the readings are equally accurate.

For accurate reference temperatures, we choose the freezing and boiling points of water.

1. *Place both thermometers into a uniform mixture of ice and water.* The thermocouple reference junction container will do. Be sure that there is plenty of ice and that it is well mixed.

2. *Record the temperature indicated by each thermometer.*

3. *Place both thermometers* in a container of gently boiling water.

4. *Record the temperature indicated by each thermometer.*

5. *If the thermocouple readings were not accurate,* correct the amplifier *Zero* and *Gain.* You can do this by repeating the procedure on page 13.

Response Time

The *response time* of a thermometer is how long it takes to change to a new temperature. In Section C we will study these changes in detail and determine a mathematical definition of response time. But, for now, we will just say that it is the approximate time it takes for the thermometer to come to the new temperature when the temperature of its surroundings changes.

You will see that several factors determine the response time. Again, in Section C we will look at some of these factors. But see if you can draw any conclusions here.

1. *Dry both thermometers* and be sure that they are at room temperature.

2. *Plunge each thermometer into cold water* and *time how long it takes* each to come to the new temperature. Use your best estimate of when the new temperature is reached.

3. *Repeat with warm water.*

4. *Repeat for air.* That is, pull the thermometer out of the water, quickly dry it, and time how long it takes to reach room temperature.

5. *Make several trials* of steps 2, 3, and 4 and *record your values* on the data page.

EXPERIMENT A-5. Thermal Contact and Size Effects

The previous experiments gave you some information on the behavior of the thermometers themselves. Now you will determine the suitability of each thermometer for measuring the case temperature of the power transistor.

The figure shows a good way of mounting the thermocouple to the case. Mounting the mercury thermometer is not so easy. The problem is in getting good *thermal contact* between the thermometer and the device whose temperature is to be measured.

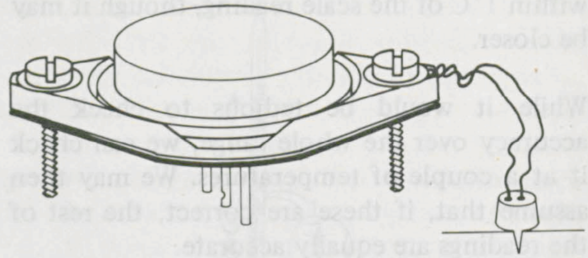


Figure 15. The thermocouple should be firmly mounted to the transistor case. One way is to clamp it under a washer on the mounting screw.

Procedure

1. *Turn on the power transistor* and adjust the current so that it is dissipating 4 W. You will have to continually adjust the current to maintain a power dissipation of 4 W as the transistor heats up.

2. *Time how long it takes* for the power transistor to reach its final temperature (it will be about 15 min). Follow the temperature rise with the thermocouple and by touching the transistor case with your finger.

3. *Record the temperature* at which the transistor gets too hot to touch, and the final (*steady-state*) temperature.

4. *Measure the case temperature with the mercury thermometer.* Do the best job you can. What clever schemes can you devise for improving the thermal contact?

5. *Record the highest temperature* you can measure with the mercury thermometer when the power transistor is dissipating 4 W.

6. *Simultaneously record the thermocouple reading.* Has it changed since you attached the mercury thermometer? How would you explain this?

7. *Sketch and/or describe* how you attached the thermometer to the transistor case for step 5.

ABOUT THE POWER TRANSISTOR

Now that you have some experience using the power transistor and observing its behavior, we will take a look at what the manufacturer says about its capabilities. This information is given on a specification sheet. The "spec" sheet for your transistor is reproduced on page 19.

In the next few paragraphs we will go over the spec sheet and describe the items that are listed there. They fall into three broad classes: mechanical specifications, which tell about the transistor's dimensions; electrical specifications, which tell about its behavior in an electrical circuit; and thermal specifications, which tell how temperature affects its performance.

General Description

In the upper left-hand box of the spec sheet there is a brief description of what the transistor is designed for and its general characteristics. The 2N3055 is a general-purpose power transistor. It is used for amplifiers that produce output currents of up to 15 A.

NPN SILICON POWER TRANSISTOR

. . . designed for general-purpose, moderate speed, switching and amplifier applications.

- DC Current Gain – h_{FE} = 20-70 @ I_C = 4.0 Adc
- Collector-Emitter Saturation Voltage – $V_{CE(sat)}$ = 1.0 Vdc (Max) @ I_C = 4.0 Adc
- Excellent Safe Operating Area

It has "moderate speed" for switching. This means that the output current can change polarity (direction of flow) fairly quickly (10^{-6} s) with sudden changes in the control current.

Current Gain

The DC current gain (h_{FE}) tells how much greater the collector current (I_C) will be for a given base current (I_B). See Figure 16. That is:

$$h_{FE} = \frac{I_C}{I_B}$$

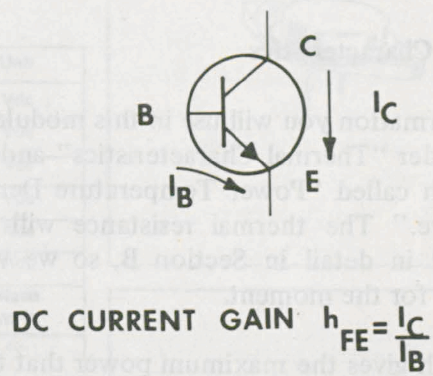


Figure 16.

The fact that the DC current gain ranges from 20 to 70, means that it will vary from transistor to transistor. The manufacturer usually gives the gain for conditions where the gain is small (I_C = 4 A), so it is not unusual to find a 2N3055 with a gain greater than 70. The gain also depends on the operating temperature, as you have seen.

If you measured h_{FE} in the optional part of Experiment A-1, compare your value to the range given in the spec sheet.

TRANSISTOR LIMITATIONS

Maximum Ratings

Various maximum ratings for voltage, current, and power are listed in the next box down on the spec sheet. Many of these have already been taken into account in your setup. For instance, note that the maximum collector-emitter voltage is 60 V*, and that your setup used a 12-V supply.

The "Total Device Dissipation" is the maximum power that the transistor can *dissipate* (get rid of without being damaged by heat), provided the case temperature is at 25°C. This value is 115 W. If the case temperature exceeds 25°C, the maximum power that can be dissipated is reduced or "derated." Guides for doing this derating are given in the following boxes in the spec sheet.

Thermal Characteristics

The information you will use in this module is given under "Thermal Characteristics" and in the graph called "Power Temperature Derating Curve." The thermal resistance will be discussed in detail in Section B, so we will bypass it for the moment.

The graph gives the maximum power that the transistor can dissipate for various case temperatures. As the case temperature rises above 25°C, the transistor power must be reduced. The greater the case temperature, the less power can be dissipated.

In your last experiment, your power transistor was dissipating 4 W. According to the graph, the case temperature could have gone to about 190°C before exceeding the curve. How close to this maximum value did you measure the case temperature to be at 4 W?

Even when no power is being dissipated in the transistor, the maximum allowable case temperature is 200°C. Note that this is also the maximum operating and storage temperature of the junction.

Above 200°C there is a good likelihood that the junction will burn up and the transistor will be destroyed.

MAXIMIZING THE TRANSISTOR CAPABILITIES

In order to utilize the 2N3055 to its fullest capability (that is, to have output currents as high as 15 A and the power transistor dissipating 115 W), we must keep the case temperature below 25°C. This is about room temperature, or the temperature of this page! To get rid of 115 W of power while keeping the case temperature at 25°C is not an easy task. In Section B we will explore the heat transfer processes and the various devices and schemes which are used to keep the temperature down.

*The two values of this voltage refer to whether or not the base-emitter is open (O), or is connected with some resistance (R).

A SPEC SHEET

NPN SILICON POWER TRANSISTOR

. . . designed for general-purpose, moderate speed, switching and amplifier applications.

- DC Current Gain — $h_{FE} = 20\text{–}70$ @ $I_C = 4.0$ Adc
- Collector-Emitter Saturation Voltage — $V_{CE(sat)} = 1.0$ Vdc (Max) @ $I_C = 4.0$ Adc
- Excellent Safe Operating Area

15 AMPERE POWER TRANSISTOR

NPN SILICON

60 VOLTS
115 WATTS

*MAXIMUM RATINGS

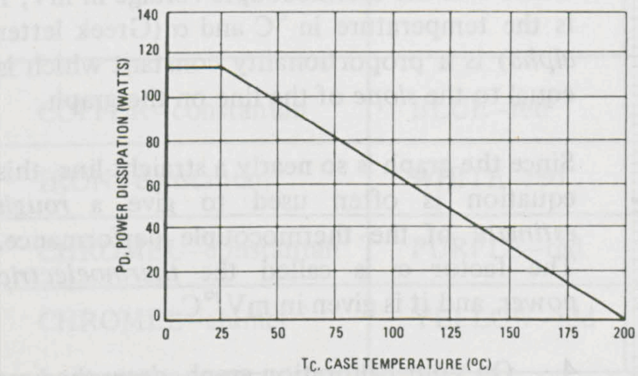
Rating	Symbol	Value	Unit
#Collector-Emitter Voltage	V_{CEO}	60	Vdc
Collector-Emitter Voltage	V_{CER}	70	Vdc
Collector-Base Voltage	V_{CB}	100	Vdc
Emitter-Base Voltage	V_{EB}	7.0	Vdc
Collector Current — Continuous	I_C	15	Adc
Base Current — Continuous	I_B	7.0	Adc
Total Device Dissipation @ $T_C = 25^oC$ Derate above 25^oC	P_D	115 0.657	Watts $W/^oC$
Operating and Storage Junction Temperature Range	T_J, T_{stg}	-65 to +200	^oC

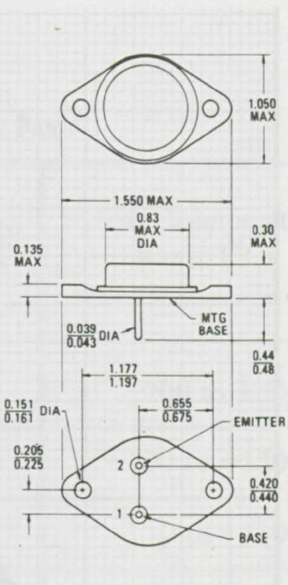
THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	θ_{JC}	1.52	$^oC/W$

*Indicates JEDEC Registered Data.
#Motorola guarantees this value in addition to JEDEC Registered Data.

FIGURE 1 — POWER TEMPERATURE DERATING CURVE





CASE 11
(TO-3)

Collector Connected to Case

Permission to use courtesy of Motorola Semiconductor Products, Inc.

ABOUT THE THERMOCOUPLE

As you have seen in your experiments, the thermocouple is a thermometer in which a voltage is generated when the junctions of two metals are placed at different temperatures. This phenomenon is called the *thermoelectric effect.*

Understanding why and how the voltage develops is a part of solid-state physics and is beyond the scope of this module. More important here is an understanding of what the voltages are, how they are described, and what use can be made of them.

Plotting the Thermocouple Voltage

As a first step you will plot a simple graph of thermocouple voltage versus temperature from the thermocouple calibration table in Appendix A. This will give you a *calibration curve.*

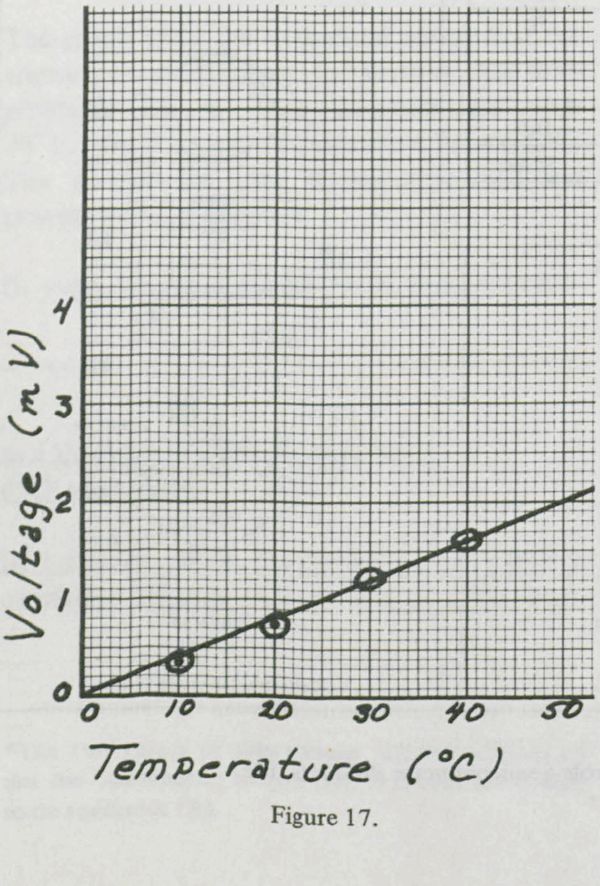


Figure 17.

1. *Label a piece of linear graph paper* with temperature as abscissa (horizontal axis) and thermocouple voltage as ordinate (vertical axis). Be sure to include your name, the date, and what the graph is about.

2. *Plot the data* from the calibration table for temperatures between 0°C and 200°C, putting in a point every 10°C, as shown in Figure 17.

3. *Draw the calibration curve.* Do the data points follow a straight line? Not quite. Therefore, you must use a sharp pencil and a draftsman's French curve to draw an accurate curve through the points.

This calibration curve can now be used instead of the table for converting your thermocouple voltages to temperature. One advantage of the curve is that it gives values of voltage and temperature which are between those given in the table.

Calculating the Thermoelectric Power

If the calibration curve were a straight line it could be described by the simple equation:

$$V = \alpha T$$

where V is the thermocouple voltage in mV, T is the temperature in °C and α (Greek letter *alpha*) is a proportionality constant which is equal to the *slope* of the line on the graph.

Since the graph is so nearly a straight line, this equation is often used to give a *rough estimate* of the thermocouple performance. The factor α is called the *thermoelectric power,* and it is given in mV/°C.

4. On your calibration graph, *draw the best straight line* you can through the points, between 0°C and 100°C. The same number of points should be above your line as below.

5. *Calculate the slope* of the line. This slope is the thermoelectric power. Compare your value to that given in the table below. (To calculate the slope, divide by the height of the line at some point–the rise–by the horizontal distance to that point–the run.)

6. *Check the deviation of your straight line* from the true curve. For example, what temperature does the straight line give at V = 0 mV, at 4.277 mV?

7. *Record your values* for steps 5 and 6 on your graph.

Using Thermoelectric Power

The importance of thermoelectric power is that it lets you calculate *roughly* the voltage you would expect from a given thermocouple for a given temperature difference. For example, if a thermocouple has a thermoelectric power of 0.05 mV/°C and the temperature difference between its junctions is 70°C, then the measured voltage will be:

$$V = \alpha\,(\Delta T)$$

$$= .05\,\frac{\text{mV}}{^\circ\text{C}} \times 70^\circ\text{C}$$

$$= 3.5\ \text{mV}$$

(Δ is the Greek letter *delta,* and it is used to mean a change or difference. Here ΔT means difference in temperature.) Or vice-versa, if the voltage is measured, α can be used to give a rough indication of the temperature without having a calibration table.

It should be noted that thermoelectric *power* is not a proper name since it really represents a *voltage* per temperature difference. However, in some applications thermocouples are used to generate power (for example to drive a switch in a thermostatic control), so the name power has stuck.

Table I. Characteristics of Thermocouple Pairs

Thermocouple Pair[1]	Color Code[2]	Thermoelectric Power (α)mV/°C (for 0–100°C)	Useful Temperature Range (°C)
COPPER–constantan	BLUE–red	0.0424	–200 to +300
IRON–constantan	WHITE–red	0.0528	–200 to +1300
CHROMEL–constantan	PURPLE–red	0.063	0 to +1100
CHROMEL–alumel	YELLOW–red	0.041	–200 to +1200

[1] The polarity of the capitalized material is positive with respect to the other material when the temperature of the measuring junction exceeds the temperature of the reference junction.

[2] Standard wire insulation color code for thermocouples.

COMPARING THERMOMETERS

Range, Accuracy and Sensitivity

In measuring the thermal characteristics of the power transistor you need a thermometer with a *range* of at most 200°C, since the transistor should never exceed that temperature.

Further, you need an *accuracy* of only ±1 or ±2°C. (The ± sign means that the true value may lie *above* or *below* your measured value.)

Look at your measured data for the mercury thermometer and for the thermocouple. Do they both meet these criteria? In particular, compare the case temperature reading that each gave at a power of 4 W. Which one is more accurate?

The *sensitivity* required is about the same as the accuracy, ±1 or ±2°C, for the same reasons. However, it is useful to define sensitivity a little more carefully. For thermocouples, the sensitivity is the inverse of the thermoelectric power. For a copper-constantan thermocouple, the sensitivity is,

$$S = \frac{1}{\alpha} = \frac{1}{.0424} \frac{°\mathrm{C}}{\mathrm{mV}}$$

$$S = 23.6 \frac{°\mathrm{C}}{\mathrm{mV}}$$

This says that for each mV change in thermocouple output, the temperature has changed by 23.6°C. The overall sensitivity is thus determined by how accurately you can measure voltage! If you can detect voltage changes, ΔV, of ±0.01 mV, then your overall sensitivity, s, is:

$$s = S \times \Delta V$$

$$= \frac{23.6°\mathrm{C}}{\mathrm{mV}} \times (\pm 0.01\,\mathrm{mV})$$

$$= \pm 0.02°\mathrm{C}$$

Response Time and Thermal Contact

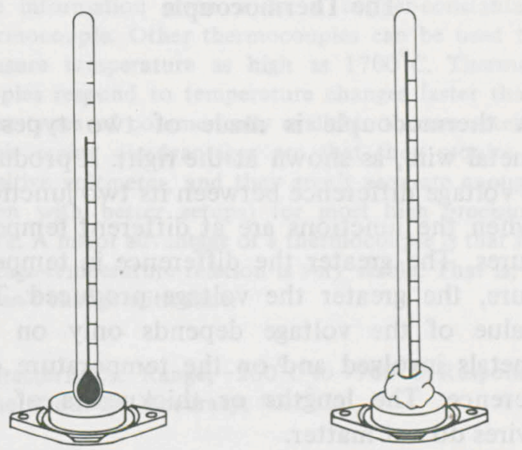
The *response time* of a thermometer depends primarily on two factors. The first is *thermal contact*; how well can heat flow from the object to the thermometer? Thermal contact can be described by a *thermal resistance* to heat flow. When electrical current flows through a resistor, there is a voltage drop with the voltage being higher on the input side. In a somewhat similar manner, when heat flows through a material (thermal resistor) there is a temperature drop, with the input side being hotter.

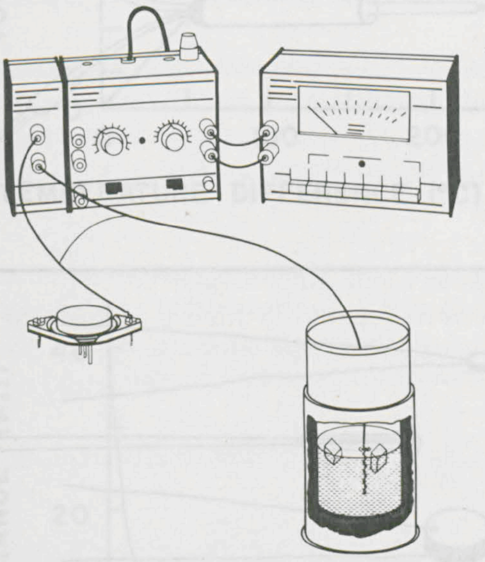
Thermal resistance will be described in detail in Section B, but to get some idea of what is involved take a look at your response-time data for air and water. Note that the response time is much longer for air than water, indicating a poorer thermal contact. Note also that it does not depend significantly on the water temperature since it is about the same for cold as for hot water.

Response Time and Size Effects

The second factor which affects the response time is *size*. There is quite a bit of mercury and glass to be heated (almost as much material as the transistor). Heating the mercury and glass removes a lot of heat from the transistor, thus reducing its temperature. The amount of heat removed from the transistor depends both on the mass involved and its *specific heat capacity*. Heat capacity will be described in Section C.

The mercury-in-glass thermometer is sufficiently accurate, but it is large and slow to respond to temperature changes. It makes poor thermal contact, which means a slow response time and an inaccurate reading. With better thermal contact, the large amount of mercury and glass takes away a lot of heat from the transistor, thus changing the temperature of what is measured.





The thermocouple doesn't affect the measurement much because it is small. It makes good thermal contact with the transistor, and responds quickly and accurately to temperature changes.

Figure 18.

Resistance Thermometers and Thermistors

There are other types of thermometers which would have worked equally well for your measurement. Among these are the *resistance thermometer* and the *thermistor*.

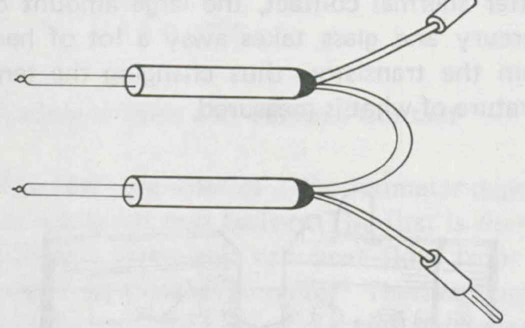
On the next two pages the characteristics of these two thermometers are compared. Verify for yourself that they have adequate capabilities. The thermistor is used in another module of the Physics of Technology series, *The Pressure Cooker*. Resistance thermometers are expensive, so they are used only when great accuracy and wide range are necessary.

THREE THERMOMETERS

Illustration

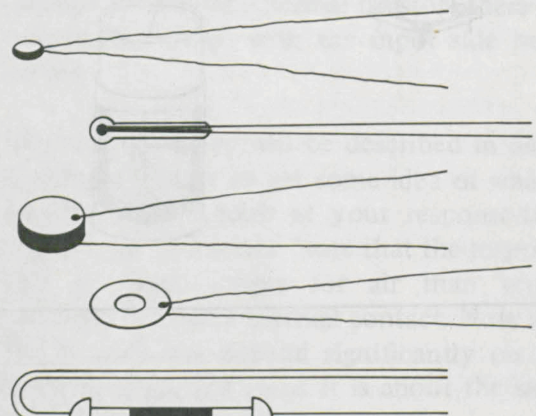
The Thermocouple

A thermocouple is made of two types of metal wire, as shown at the right. It produces a voltage difference between its two junctions when the junctions are at different temperatures. The greater the difference in temperature, the greater the voltage produced. The value of the voltage depends only on the metals involved and on the temperature difference. The lengths or thicknesses of the wires do not matter.



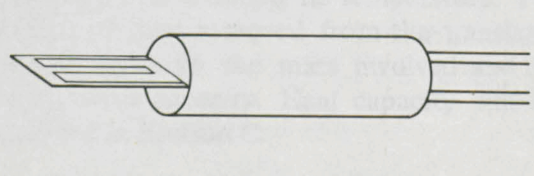
The Thermistor

A thermistor is a kind of resistor. Its resistance *decreases* as its temperature increases. The material it is made of is a type of semiconductor. This same sort of material is used to make transistors and diodes. There are many shapes and sizes of thermistors. The resistance of each depends on its size, as well as on the type of material used to make it.

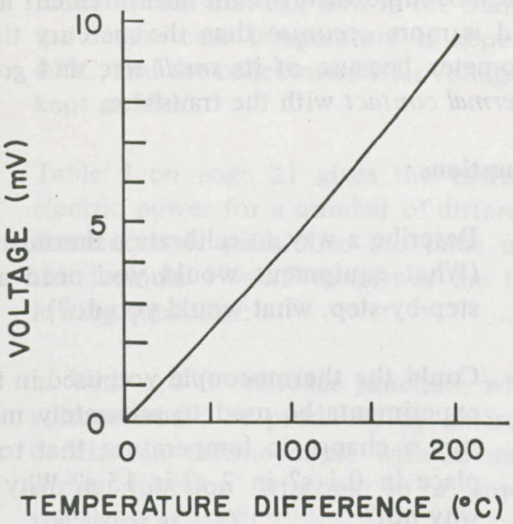


The Resistance Thermometer

A resistance thermometer is similar to a thermistor, except that its resistance *increases* as the temperature increases. Instead of being made of a semiconductor material it is usually a metal, such as platinum or nickel. The one illustrated at the right is a simple variety; for more exact work, the wire is specially mounted and enclosed in an air-tight case. Other kinds of mountings are also used, but the operating principles are the same in all cases.

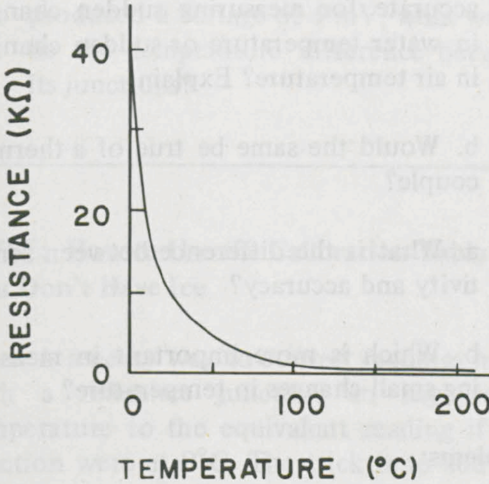


Calibration Graph	Comments



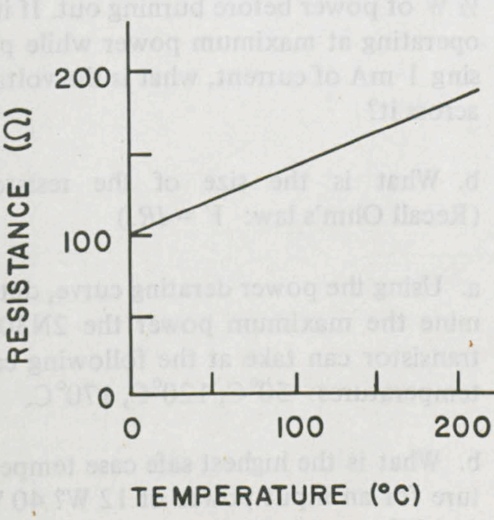
The information given is for a copper-constantan thermocouple. Other thermocouples can be used to measure temperature as high as 1700°C. Thermocouples respond to temperature changes faster than most types of commerically available thermometers. Their major disadvantages are that they require a sensitive voltmeter, and they aren't accurate enough (even with better setups) for most high precision work. A major advantage of a thermocouple is that its voltage-temperature relation is very stable. That is, it doesn't change with time.

Characteristics: Range, −260°C to +900°C; Response Time, about 2 s; Accuracy, ±0.2°C.



The information given is for a typical, commercially made thermistor. Various types of thermistors can be used for measuring temperatures near absolute zero (−273°C), and they can be made (with a bit of effort) to have response times of about 10^{-3} s. A major difficulty with thermistors is that, unless they are properly aged, they must be calibrated frequently. In spite of this, their ease of use and high sensitivity (large change in resistance for a small change in temperature) make them widely used.

Characteristics: Range, −60°C to +300°C; Response Time, several seconds; Accuracy, depends on the temperature.



The information given is for a platinum-resistance thermometer. When properly mounted, a platinum thermometer is accurate enough to be used as a temperature *standard*. Resistance thermometers with this accuracy are quite expensive. They also require a "resistance bridge" for accurate resistance measurements. The resistance increases linearly with temperature. (In other words, the graph of resistance and temperature is a straight line.) This is true to within better than 0.2% over the range of temperatures used in this module (0°C to 200°C). It is almost as linear outside this range. This makes it easy to accurately convert resistance readings to temperature.

Characteristics: Range, −250°C to +800°C; Response Time, about 1 s; Accuracy, ±0.2°C.

REVIEW

Summary

Power is energy per unit time. Power is measured in watts. One watt (W) is one joule per second (J/s).

The electrical power into or out of a component of an electrical circuit is:

$$P = VI$$

where V is the voltage across the component in *volts,* and I is the current flowing through it in *amperes.*

To keep power transistors, engines, and other systems at a low enough temperature to operate properly, the portion of the power which is turned into thermal energy (heat) must be *dissipated* to the surroundings.

The first experiment of this section showed that the power transistor's characteristics, such as its *gain,* depend strongly on the temperature. To keep the characteristics constant, the temperature must be kept constant.

Heating occurs when chemical, mechanical, electrical, or some other form of energy is converted into *thermal energy* by some process.

Temperature is a measure of "hotness" or "coldness" and can be measured by many different devices, called *thermometers.* Liquid-in-glass thermometers, resistance thermometers, thermistors, and thermocouples are examples of such devices.

The *thermocouple* creates a voltage which depends on the temperature difference between two junctions of unlike metals. This voltage is converted to temperature readings by the use of *calibration tables.*

Thermocouples *respond more quickly* to temperature changes than does a common mercury-in-glass thermometer. Also the thermocouple disturbs the measurement less, and is more *accurate* than the mercury thermometer because of its *small size* and *good thermal contact* with the transistor.

Questions

1. Describe a way to calibrate a thermistor. (What equipment would you need and step-by-step, what would you do?)

2. Could the thermocouple you used in the experiments be used to accurately measure a change in temperature that took place in 0.1 s? in 2 s? in 15 s? Why or why not?

3. a. Is a mercury thermometer more accurate for measuring sudden changes in water temperature or sudden changes in air temperature? Explain.

   b. Would the same be true of a thermocouple?

4. a. What is the difference between sensitivity and accuracy?

   b. Which is more important in measuring small changes in temperature?

Problems:

1. a. A standard ½-W resistor can dissipate ½ W of power before burning out. If it is operating at maximum power while passing 1 mA of current, what is the voltage across it?

   b. What is the size of the resistor? (Recall Ohm's law: $V = IR$.)

2. a. Using the power derating curve, determine the maximum power the 2N3055 transistor can take at the following case temperatures: 50°C, 120°C, 170°C.

   b. What is the highest safe case temperature for an input power of 12 W? 40 W? 116 W?

3. Using the derating curve, find the maximum current that can flow in the transistor if the case temperature is kept at 45°C, and the collector-emitter voltage is kept at 40 V.

4. Table I on page 21 gives the thermoelectric power for a number of different thermocouple pairs. Use the table and the formula $V = \alpha T$ to answer the following questions:

   a. With a 0°C reference junction, what voltage would be produced by an iron-constantan thermocouple with its measuring junction attached to a power transistor at 100°C?

   b. If a chromel-alumel thermocouple produced a voltage of 4 mV, what would be the temperature difference between its junctions?

   c. If a chromel-constantan thermocouple is used to turn on a control switch when the temperature difference is 900°C, what voltage output does it produce?

   If the switch requires a current of 0.5 A, what is the maximum resistance it may have?

5. A 2N3055 transistor has a chromel-constantan thermocouple attached to it. The thermocouple has a reference junction at 20°C (room temperature), and the voltage between the junctions is 2.5 mV.

   a. What is the transistor temperature?

   b. What is the maximum power that could safely be dissipated by the transistor? (See note below.)

NOTE: How to Use the Calibration Table if You Don't Have Ice

There is an easy way to convert readings made with a reference junction at, say, room temperature to the equivalent reading if the junction were at 0°C. The trick is to add the voltage corresponding to the reference junction temperature (as measured using a thermometer, perhaps) to the meter reading before you use the chart.

For example, suppose the reference junction is at 20°C. Checking the table, this corresponds to 0.787 mV. If the meter reading is 4 mV, then look at the chart for the value $4 + 0.787 = 4.787$ mV. The temperature of the other junction is thus 111°C.

3. Using the derating curve, find the maximum current that can flow in the transistor if the case temperature is kept at 45°C, and the collector-emitter voltage is kept at 40 V.

4. Table 1 on page 21 gives the thermoelectric power for a number of different thermocouple pairs. Use the table and the formula $V = bT$ to answer the following questions:

a. With a 0°C reference junction, what voltage would be produced by an iron-constantan thermocouple with its measuring junction attached to a power transistor at 100°C?

b. If a chromel-alumel thermocouple produced a voltage of 4 mV, what would be the temperature difference between its junctions?

c. If a chromel-constantan thermocouple is used to turn on a control switch when the temperature difference is 900°C, what voltage output does it produce?

d. If the switch requires a current of 0.5 A, what is the maximum resistance it may have?

5. A 2N3055 transistor has a chromel-constantan thermocouple attached to it. The thermocouple has a reference junction at 20°C (room temperature), and the voltage between the junctions is 5.5 mV.

a. What is the transistor temperature?

b. What is the maximum power that could safely be dissipated by the transistor? (See note below.)

NOTE: How to Use the Calibration Table if You Don't Have Ice

There is an easy way to convert readings made with a reference junction at, say, room temperature to the equivalent reading if the junction were at 0°C. The trick is to add the voltage corresponding to the reference junction temperature (as measured using a thermometer, perhaps) to the meter reading before you use the chart.

For example, suppose the reference junction is at 20°C. Checking the table, this corresponds to 0.787 mV. If the meter reading is 4 mV, then look at the chart for the value 4 + 0.787 = 4.787 mV. The temperature of the other junction is thus 111°C.

SECTION B

Heat Transfer Processes

There are several processes by which heat can flow from one place to another, and each is characterized by its own *thermal resistance.* Therefore, the first step is to understand these processes and how they operate. Then we can more easily determine what factors contribute to the thermal resistance for each process, and which of these we can change.

The thermal resistance to heat flow is one of the main factors that determine the time behavior of a thermal system. This means that one way to control the final temperature and how fast the transistor reaches it is to change the thermal resistance.

Figures 19, 20, and 21 depict familiar examples of the three main processes by which heat is transported. Try to think of others.

CONDUCTION

Conduction is the process by which heat flows *through materials.* When one part of an object is hotter than another the thermal energy is *conducted* through the material to the colder part.

As you well know, some materials are better thermal conductors than others. Metals are particularly good conductors of heat and are used where high heat conduction is desired.

Materials that don't conduct heat well, such as styrofoam, wood and cloth, are called *insulators.* They are used where low heat conduction is desired.

CONVECTION

Convection is the process by which heat is carried by a *moving fluid* from one place to another. When a wind blows, you usually feel cooler. Your body heat is being convected away by the moving air.

In some applications the moving fluid may be water, as in the cooling system of your car. Some nuclear reactors even use a liquid metal (sodium) for cooling.

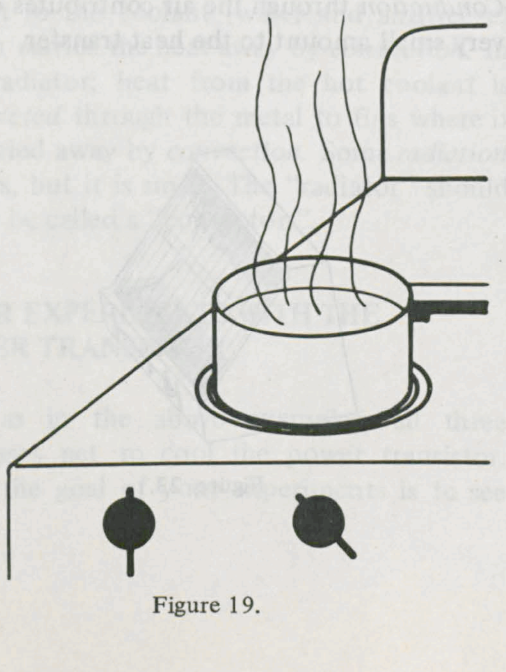


Figure 19.

Figure 20.

RADIATION

Radiation is the process by which heat is transported across empty space. Even when there are no objects or fluids around to conduct or to convect heat, heat can still "flow" by radiation.

For example, the sun heats the earth across the nearly perfect vacuum of space. It *radiates* a great amount of heat due to its high temperature. In heat radiation, energy is transferred by *electromagnetic waves.*

Figure 21.

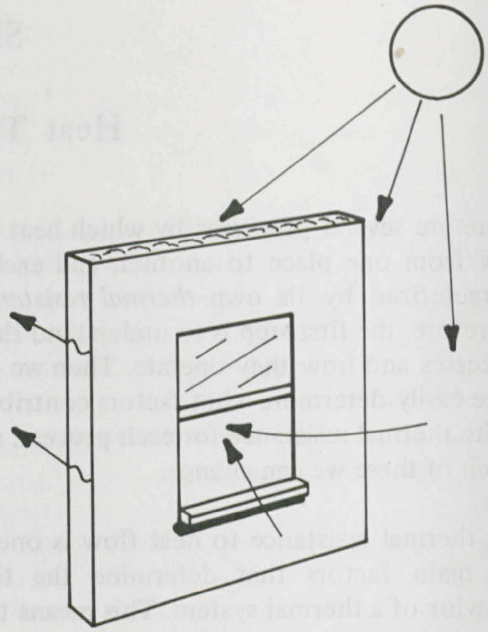


Figure 22.

SOME COMMON EXAMPLES

In most real situations all three processes operate together as indicated in the following examples.

Houses

On a hot day, heat is *conducted* into the house through the walls. On a cold day, the transfer goes the other way.

The sun's rays transfer heat to the house by *radiation.* At night the house radiates heat to the sky.

Air moving by the house or through open windows and "leaky" areas transfers heat by *convection.*

Electric Heaters

An electric heater *radiates* heat. A fan is often used to improve heat transfer by *convection. Conduction* through the air contributes only a very small amount to the heat transfer.

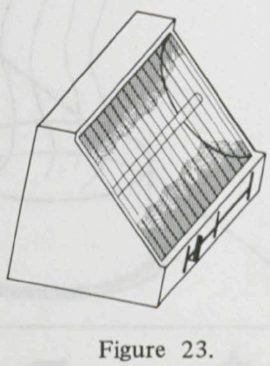


Figure 23.

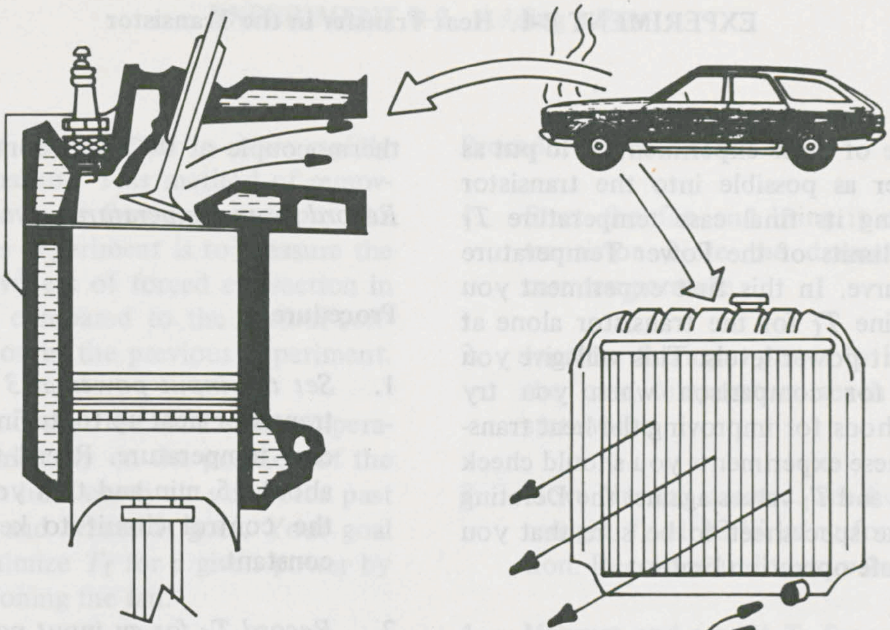


Figure 24.

Automobiles

The cooling system in an auto must function efficiently to keep the engine from overheating. The heat transfer processes which occur include all three basic types.

The spark ignites the air-gasoline mixture which the piston has compressed. Chemical energy is the energy input. Hot gases escape in the exhaust stroke; this is *convective* cooling. Heat is *conducted* through the cylinder walls to get to the coolant (water and antifreeze) which carries the heat away by *convection.* In the radiator, heat from the hot coolant is *conducted* through the metal to fins where it is carried away by *convection.* Some *radiation* occurs, but it is small. The "radiator" should really be called a "convector."

YOUR EXPERIMENTS WITH THE POWER TRANSISTOR

Just as in the above examples, all three processes act to cool the power transistor. Thus the goal of your experiments is to see which processes are going on, where they occur, and what you can do to increase the amount of heat each can carry away.

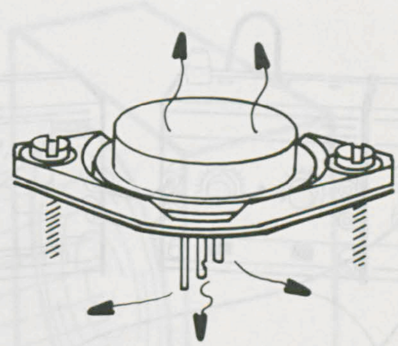


Figure 25.

According to the spec sheet, in order to utilize the power transistor to its fullest capability, these processes must carry away 115 W of power while maintaining the case temperature at 25°C or less. You will see how well you can do.

EXPERIMENT B-1. Heat Transfer in the Transistor

The purpose of these experiments is to put as much power as possible into the transistor while keeping its final case temperature T_f within the limits of the Power Temperature Derating Curve. In this first experiment you will determine T_f for the transistor alone at two different power levels. This will give you base data for comparison when you try various methods for improving the heat transfer. In all these experiments you should check your power and T_f values against the Derating Curve of the spec sheet to be sure that you are within safe operation limits.

Preparation

Set up and check the power transistor circuit as you did in Experiment A-1.

Calibrate the amplifier/meter for the thermocouple. Use an ice-water bath and check the thermocouple at 0°C and room temperature.

Record room temperature.

Procedure

1. *Set the input power at 3 W* and let the transistor heat up to its final steady-state case temperature. Recall that this takes about 15 min and that you must adjust the control circuit to keep the power constant.

2. *Record T_f for an input power of 3 W* in the space provided on the data page.

3. *Increase the input power to 5 W* and let the case reach its new steady temperature. Again this takes about 15 min.

4. *Record T_f for an input power of 5 W.*

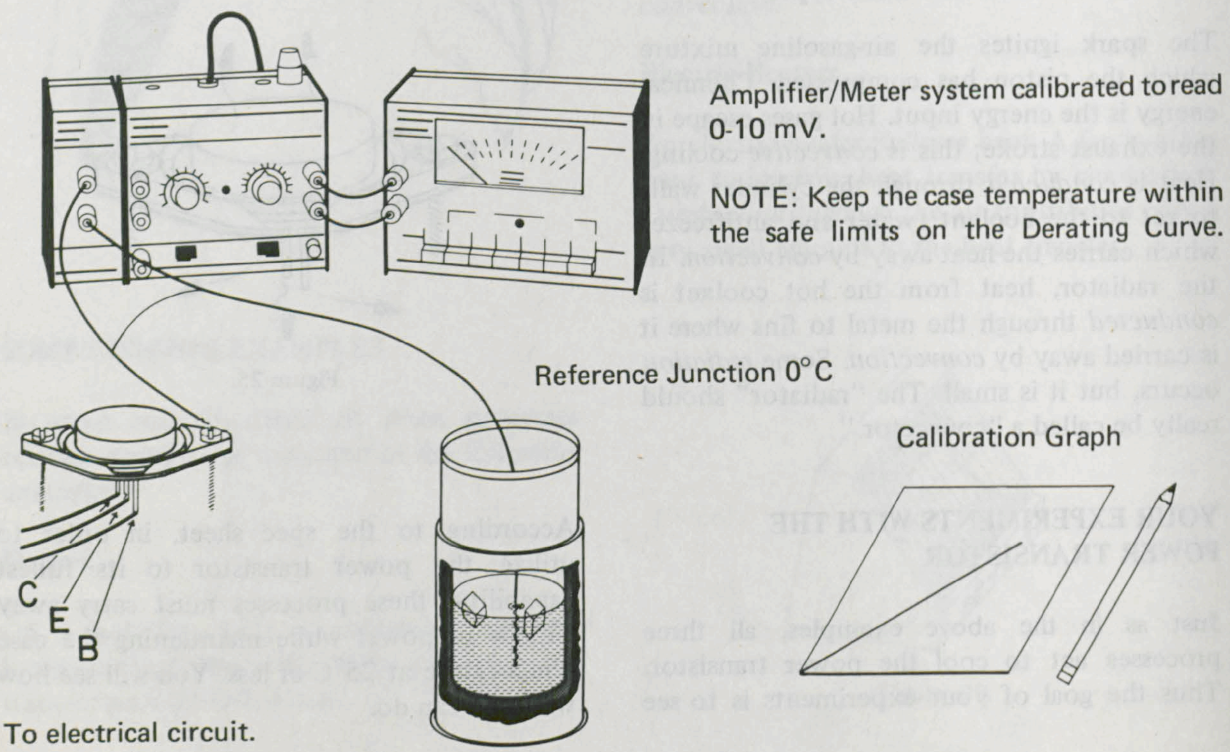


Figure 26.

EXPERIMENT B-2. Adding a Fan

With a fan you can force air to move rapidly across the transistor. This method of removing heat is known as *forced convection.* The purpose of this experiment is to measure the relative effectiveness of forced convection in removing heat compared to the *natural convection* going on in the previous experiment.

You should find that the final case temperature depends critically on the position of the fan; that is, on how much air you force past the transistor and where it goes. Your goal will be to minimize T_f for a given power by properly positioning the fan.

You will also find that the time it takes for a transistor to reach its steady-state temperature (response time) will be much shorter than without the fan. This shows that response time depends on the processes of heat transfer.

Procedure

1. Start the fan and bring it close to the transistor. Note the dramatic drop in case temperature.
2. Increase the input power to 12 W and let the case temperature reach its steady-state value.
3. Move the fan around. See how low you can get T_f at 12 W using forced convection. Record your lowest value of T_f.
4. Measure and record T_f for several power inputs less than 25 W.
5. Turn off the power.

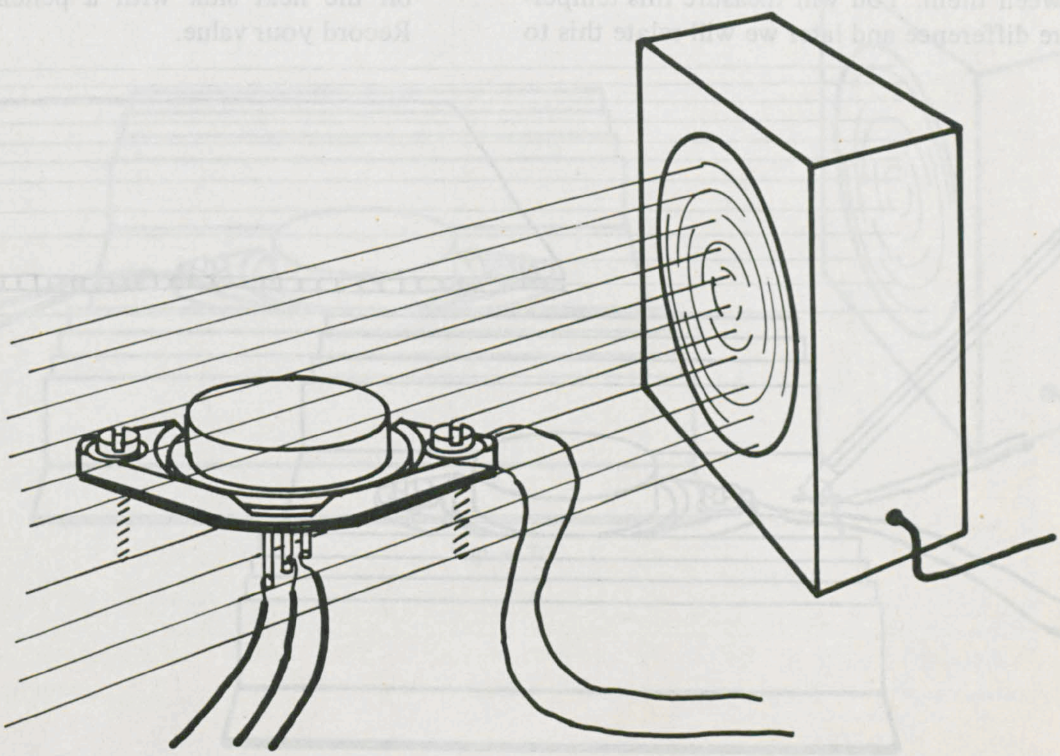


Figure 27.

EXPERIMENT B-3. Adding a Heat Sink

A *heat sink* is a device specifically designed to increase the heat flow from the transistor to the air. Its design is based on optimizing each of the heat transfer processes.

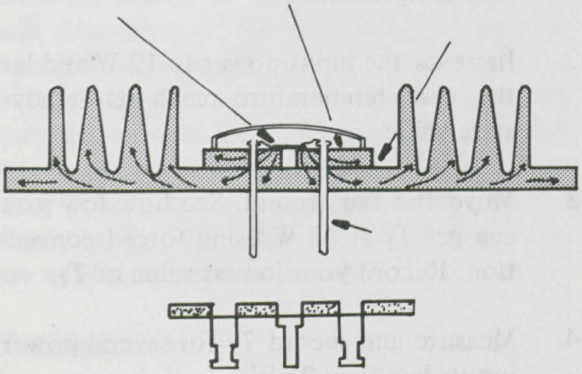


Figure 28.

In order for the heat sink to be effective there must be good thermal contact between it and the transistor where the heat is developed. One measure of the thermal contact is the temperature difference across the boundary between them. You will measure this temperature difference and later we will relate this to a better measure of thermal contact, *thermal resistance.*

Be sure the power supply is turned off. Then *mount the power transistor on the heat sink* with the thermocouple attached. *Be sure you line up all the holes.*

Procedure

1. Set the power input to 30 W and let the case temperature come up to its final steady-state value. *Be sure to keep the power constant.*

2. Record T_f on the data page.

3. Cover the transistor with a piece of cardboard. Does the temperature change? What process have you affected?

4. Carefully remove the thermocouple and measure the heat sink temperature by holding the thermocouple down *firmly* on the heat sink with a pencil eraser. Record your value.

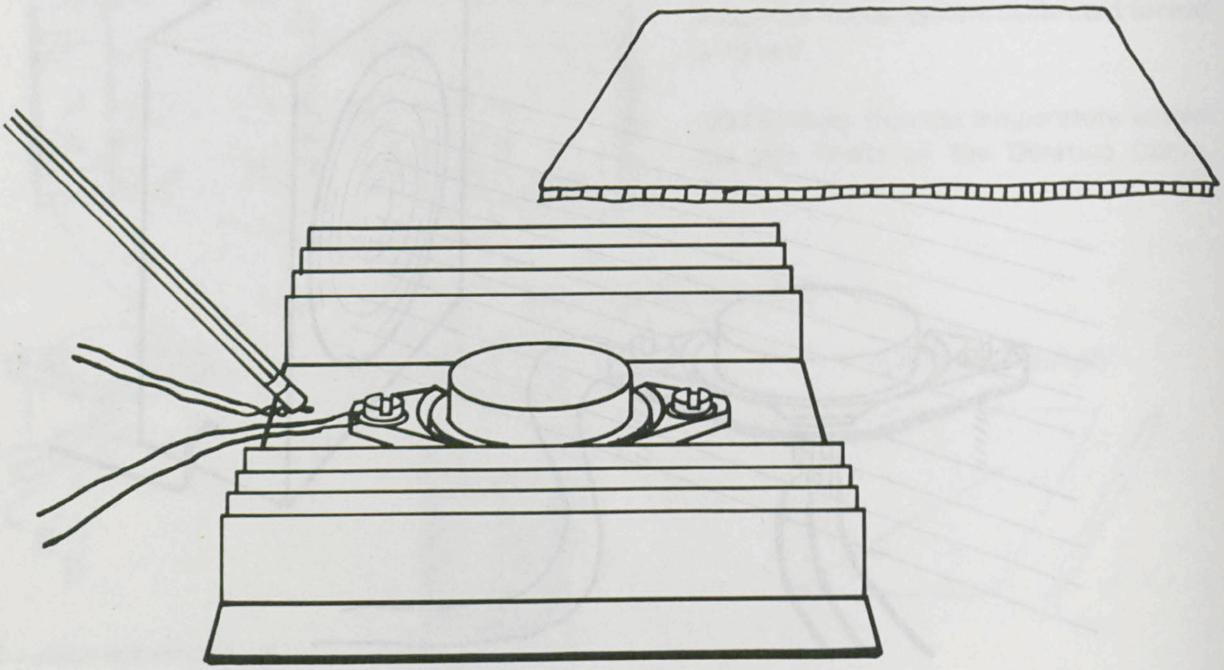


Figure 29.

EXPERIMENT B-4. Using Both a Heat Sink and Fan

When you use a fan *and* a heat sink you do as much as you can in a simple way to increase the heat flow from the transistor to the air. Any further improvement requires considerably more effort. For example, the next step might be to use water rather than air as the substance which is forced to flow past the heat sink. This, of course, would have to be done carefully so that the electrical parts of the circuit do not get wet.

You will find again in this experiment that using a fan considerably reduces the time required to reach the steady-state value of T_f. Therefore, you should be able to take several power and T_f values for this setup. From these data you will be able to determine how close you come to achieving the maximum capabilities of this power transistor.

Keep the input power at 30 W.

Reattach the thermocouple under the washer. *Place the fan close to the heat sink,* blowing *along* the fins as shown.

Procedure

1. Turn on the fan and move it around until you have minimized T_f for an input power of 30 W.

2. Record T_f on the data page.

3. Measure and record T_f for several *safe* power levels for the same fan position.

4. Turn off all systems.

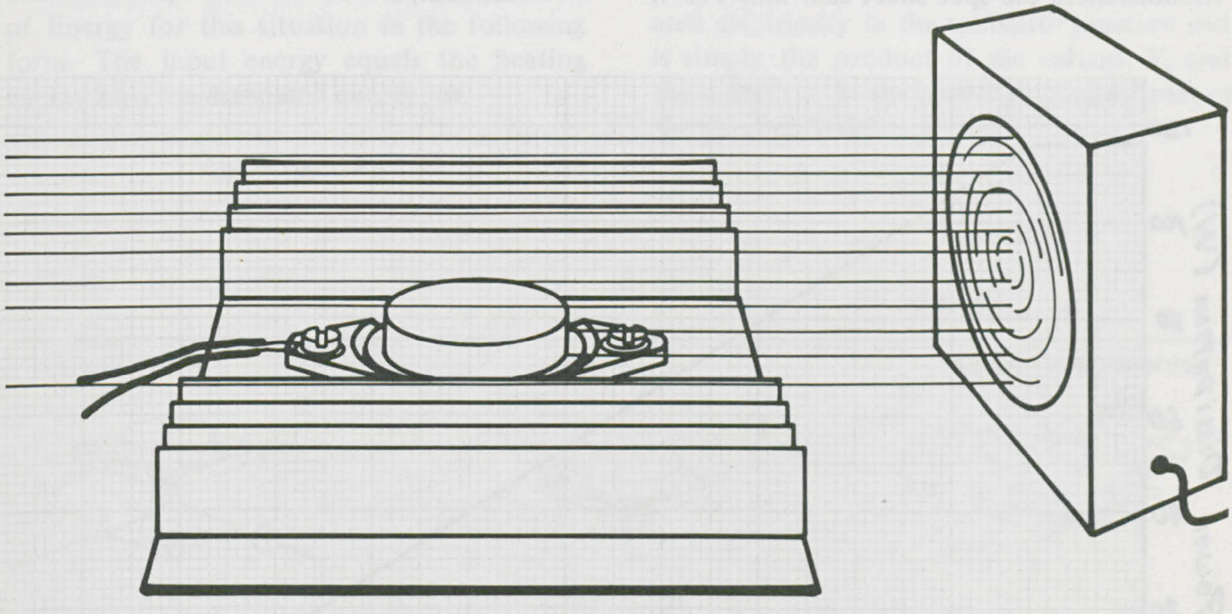


Figure 30.

ANALYZING YOUR DATA

In the four experiments of Section B you have done a rather extensive analysis of the behavior of the case temperature of a power transistor under varying conditions. There were several purposes to these experiments and several useful pieces of information which can be derived from the results.

As usual the first step to understanding this information is to plot the data on graph paper. From the graphs you can more easily see the effects of using the heat sink and fan, and the relative importance of the various heat transfer processes.

Maximizing the Power Dissipation

One important purpose of these experiments is to learn how to maximize the power that could be put into the transistor without exceeding its thermal ratings. Under the best circumstances the spec sheet said that 115 W could be dissipated. A simple way to see how well you did, is to carefully plot your experimental results on the Power Temperature Derating Curve. Follow the procedure below.

1. *Graph the Power Temperature Derating Curve* of the spec sheet on a piece of graph paper.

2. *Plot your values of input power and measured T_f* on the *same* piece of graph paper labeling the points so that you can tell the two curves apart.

3. *Draw a straight line* through each set of points and the point $P = 0$, and $T_c = T_{air}$.

4. *Determine the maximum power and case temperature* that you can safely use for each setup. This is where each line intersects the Derating Curve. Could you have safely dissipated 115 W with any of the setups?

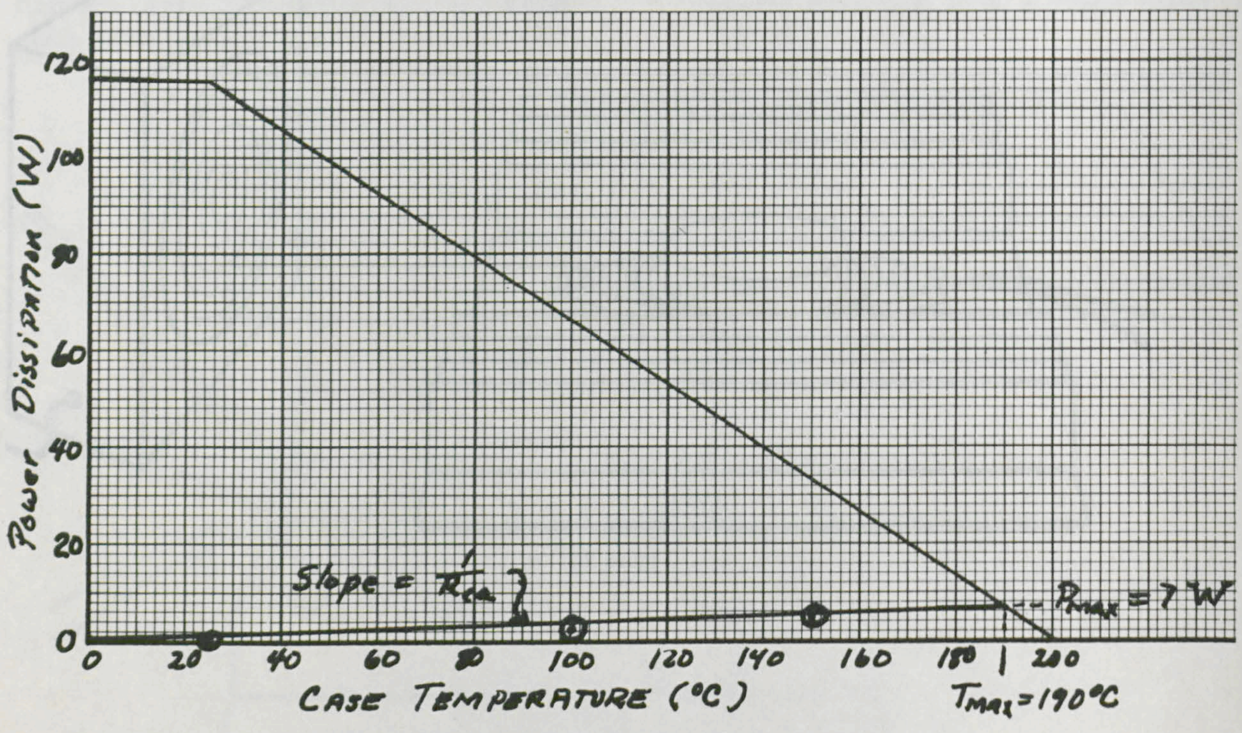


Figure 31.

ENERGY CONSERVATION IN THE POWER TRANSISTOR

The explanation of your experimental results lies in the physics of heat transfer. To describe heat transfer we will begin with the fundamental law of nature which governs its behavior, the *Law of Conservation of Energy*. This law, applied to the power transistor, leads to an equation which will predict the final steady-state temperature for any power input. In Section C it will also be seen to give the temperature at any time, even during the heating and cooling periods.

The Law of Conservation of Energy states that energy is neither created nor destroyed, it simply changes form. For the power transistor this means that the electrical energy supplied to the transistor by the power supply must all be accounted for. This input energy is partly used to heat up the transistor and the rest is dissipated as heat to the surroundings.

Thus we may write the Law of Conservation of Energy for this situation in the following form. The input energy equals the heating energy plus the dissipated energy, or

$$E_{in} = E_h + E_d$$

Since power is just energy per unit time, divide the energy equation by time to get

$$P_{in} = P_h + P_d$$

This is really a much more useful equation.

Steady-State Behavior

In Section B we are concerned with the final, steady-state behavior. Under these conditions, the case temperature is constant at T_f. Since the heating term P_h describes the heating (or cooling) process when the temperature of the transistor is changing, it is zero during the steady state. Thus for the steady state, the Law of Conservation of Energy simplifies to:

$$P_{in} = P_d$$

Input Power

In order to use this equation we must have formulas for each of the terms. The simplest of the two terms is the input power. As you saw in Section A, the input power is generated electrically in the transistor junction and is simply the product of the voltage, V, and the current, I, in the collector–emitter part of the circuit. That is:

$$P_{in} = VI$$

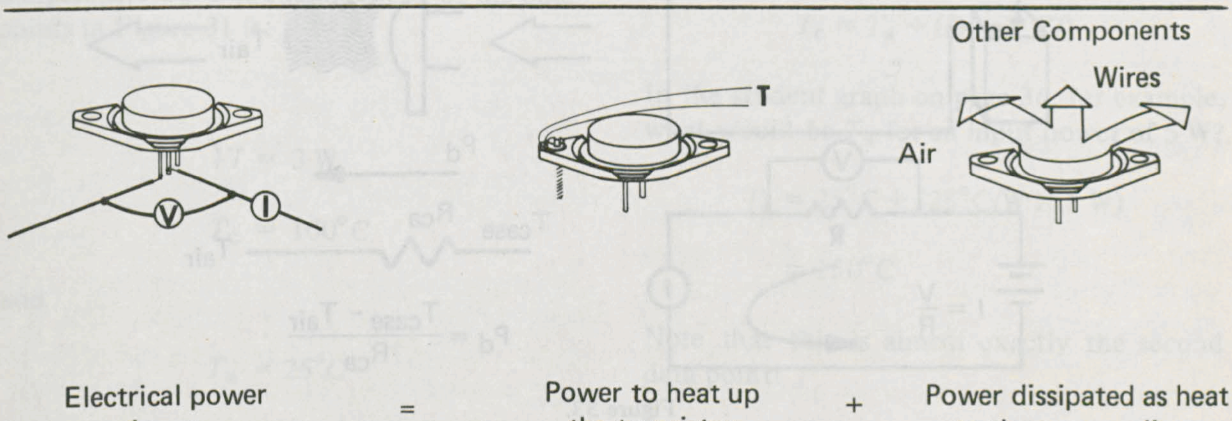


Figure 32.

Dissipated Power

Dissipated power is more difficult to describe. It will be a help to you to compare the flow of thermal energy in a thermal circuit to the flow of electrical current in an electrical circuit. While there are important differences between the two situations, the comparison helps one to remember the results.

In an electrical circuit, Ohm's Law states that the current is given by:

$$I = \frac{V}{R}$$

I represents a flow of charge per unit time and V is the potential difference (voltage) that exists across part of a circuit with electrical resistance, R.

If one thinks of *power* as a heat current (flow of energy per unit time), then the thermal equivalent of Ohm's Law is:

$$P = \frac{T_A - T_B}{R}$$

where $T_A - T_B$ is the *temperature difference* between points A and B, and R is the *thermal resistance* between the same points. Since power is in watts and temperature in degrees Celsius, the thermal resistance has the units °C/W.

There are other similarities between electrical and thermal circuits. The amount of power that flows is directly proportional to the temperature *difference* just as the current flow is directly proportional to the potential difference. Both resistances depend on the material used, the amount of flow, and the difference in temperature or in potential.* Thermal resistances add just like electrical resistances, both in series and in parallel.

When the hot transistor is surrounded by cooler air, the power dissipated by the transistor case to the air is:

$$P_d = \frac{T_{case} - T_{air}}{R_{ca}}$$

where R_{ca} is the thermal resistance between the case and the air. The transistor case and the air are at temperatures T_{case} and T_{air}, respectively.

*Both electrical and thermal resistance also depend slightly on temperature, but we shall use the approximation that they are constant.

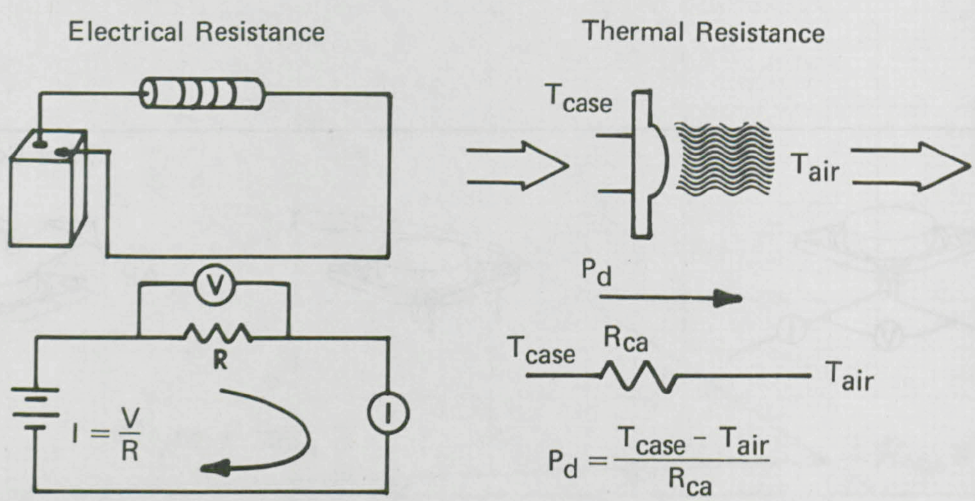


Figure 33.

USING THE ENERGY CONSERVATION EQUATION

The energy conservation equation states that

$$P_{in} = P_d$$

We now have formulas for both P_{in} and P_d. Substituting these expressions into the energy conservation equation, we get an equation which describes the *steady-state behavior.*

$$VI = \frac{(T_c - T_a)}{R_{ca}}$$

All the terms in this equation are known except R_{ca}. However, R_{ca} can be determined from your experimental data. Once R_{ca} is determined, this same equation can be used to calculate the steady-state case temperature for any input power.

Thermal Resistance

By turning the energy conservation equation around we get an expression for the *thermal resistance*:

$$R_{ca} = \frac{(T_c - T_a)}{VI}$$

This says that the thermal resistance can be calculated from any measured power input *VI,* the final case temperature T_c, and the air temperature T_a. For example, one of the data points in Figure 31 is:

$$VI = 3\text{ W}$$

$$T_c = 100°\text{C}$$

and

$$T_a = 25°\text{C}$$

Therefore the thermal resistance is:

$$R_{ca} = \frac{100°\text{C} - 25°\text{C}}{3\text{ W}}$$

$$= 25°\text{ C/W}$$

It should be noted that the thermal resistance is also related to the slope of the lines you drew on the Derating Curve. Recall that the slope of a line is the rise divided by the run. For your lines, the rise is the power *VI,* and the run is the temperature difference ($T_c - T_a$), so that:

$$\text{Slope} = \frac{VI}{(T_c - T_a)}$$

$$= \frac{1}{R_{ca}}$$

Thus one goal of your experiment was to increase the slope of this line so that it intersects the Derating Curve at as low a temperature as possible. This is equivalent to minimizing the thermal resistance from the case to the air.

Steady-State Case Temperature

With R_{ca} known, the conservation equation can be used to predict the steady-state case temperature T_c for any input power. Solving the conservation equation for T_c gives:

$$T_c = T_a + (R_{ca} \times VI)$$

In the student graph on page 36, for example, what would be T_c for an input power of 5 W?

$$T_c = 25°\text{C} + (25°\text{C/W} \times 5\text{ W})$$

$$= 150°\text{C}$$

Note that this is almost exactly the second data point!

Thermal Resistance in the Transistor

Since the thermal resistance is the primary factor that determines the rate of heat flow, it is important to know what thermal resistances are involved and how large they are. In the following we explore a number of them.

Case-Air Resistance

The most important thermal resistance is that between the case and the air since it is the only one you can change.

1. *Calculate the case to air thermal resistance* R_{ca} for each power and T_f value for each of your setups. Record your values in the space provided on the data page. Our mathematical analysis stated that R_{ca} should be a constant for each setup, independent of the input power. Was that true for your experimental results?

When you used a heat sink and fan you had done as much as possible to minimize R_{ca}. However, this probably did not let you safely dissipate 115 W. One possible improvement would be to lower the temperature of the air surrounding the transistor. Small "thermoelectric" refrigerators are available for this purpose.

2. *Calculate the air temperature* necessary to safely dissipate 115 W for your lowest value of thermal resistance.

Junction-Case Resistance

Up to now we have ignored the fact that the input energy is really developed in the transistor junction. The heat must flow from the junction to the case, and there is a thermal resistance to this heat flow. This resistance is given in the spec sheet as the junction-to-case thermal resistance, θ_{jc}, (or R_{jc} in our symbols).

3. *Find* R_{jc} *and compare it to your values of* R_{ca}. Note that, when you added the heat sink and fan R_{ca} dropped below R_{jc}.

4. *Calculate the inverse of the slope of the Derating Curve.* The inverse of the slope is the run divided by the rise.

5. *Compare your result to* R_{jc}. From this comparison you can see how the Derating Curve is determined.

Case-Sink Resistance

When you attached the transistor to the heat sink, we stressed the importance of having good thermal contact. One measure of the thermal contact is the thermal resistance. The lower the thermal resistance the better the thermal contact and the more easily the heat can flow.

6. *Calculate the thermal resistance between the case and heat sink.* Assume that all of the input power went across this resistance to be dissipated by the heat sink.

To decrease thermal contact resistance, *thermal joint compound* is available. This is a grease which is spread between two surfaces and touches both. Since it is a better conductor of heat than air separating the surfaces, it improves the thermal contact.

HEAT TRANSFER PROCESSES

The most important purpose of these last experiments was to get some experience with the three heat transfer processes, conduction, convection and radiation. All three of these processes carried some heat away from the transistor case, but they were not all equally effective.

The heat sink and fan were used to maximize the transfer of heat from the case to the air. Their use was determined from an analysis of the factors which affect the heat transfer in each process. To understand these features we need to understand how each process operates.

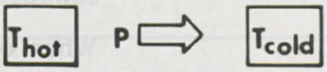
In the next few pages we shall present a "picture" of each of the heat transfer processes. Each leads to a simple mathematical relation of the form:

$$P = \frac{(T_{\text{hot}} - T_{\text{cold}})}{R}$$

where P is the thermal power that will flow from a hot region at temperature T_{hot} to a colder region at temperature T_{cold}, and R is the thermal resistance.

Thus the power that flows is directly proportional to the *temperature difference,* $(T_{\text{hot}} - T_{\text{cold}})$. It is the *thermal resistance* which determines *how fast* thermal energy will flow for a given temperature difference. By understanding what factors determine R, we shall see what one must do to decrease R for each process.

There are three main processes by which heat can flow from a hotter region to a colder region, conduction, convection, and radiation.



The total heat flow is the sum of that due to these three processes:

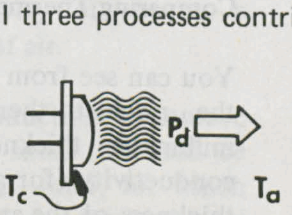
$$P_d = P_{\text{cond}} + P_{\text{conv}} + P_{\text{rad}}$$

The thermal power that flows can be described by a mathematical expression of the form:

$$P = \frac{(T_{\text{hot}} - T_{\text{cold}})}{R}$$

The thermal resistance R includes all the factors which determine how much heat flows by each process.

In the power transistor, all three processes contribute to the power dissipated from the case to the air.



$$P_d = \frac{(T_c - T_a)}{R_{ca}}$$

R_{ca} includes the thermal resistance for the three processes R_{cond}, R_{conv}, R_{rad}.

Figure 34.

CONDUCTION

Heat conduction is the process by which thermal energy is transferred from one part of an object to another part which is at a lower temperature with no motion of the object.

Two elements of this definition should be noted. First heat is always conducted from a place at a higher temperature to one at a lower temperature. This defines the *direction* of heat flow.

Second, there is no flow of matter; only energy. This is an important difference between conduction and convection.

A "Model" for Conduction

Physicists often like to speak in terms of a "model" for a particular process. By this they usually mean a simplified mental picture of something which is too complicated to understand in detail.

To develop a simple model of conduction, consider the rectangular block of material shown in Figure 35. One side of it is at a high temperature, T_h, and the other side is at a colder temperature, T_c. Heat flows from the hot side through the material to the cold side.

If the two temperatures are kept constant, the amount of heat flowing through the slab depends on several factors. First, it depends on the size of the slab: the greater the area (A) of the block the more power will flow, but the greater the length (L) of the block, the less power will flow. Also, different materials conduct heat at different rates; a piece of copper is a much better conductor than a piece of wood the same size. An appropriate constant, called the *thermal conductivity* and given the symbol k, is associated with each material. The greater the value of k, the greater the ability of the material to conduct heat. Table II compares the thermal conductivities of some common materials.

When one combines all of the above factors, the result is an equation for the thermal power conducted through the slab:

$$P_{\text{cond}} = \frac{kA}{L}\,(T_h - T_c)$$

For more on this equation, and for a formula for the thermal resistance for conduction, see the optional discussion at the end of this section.

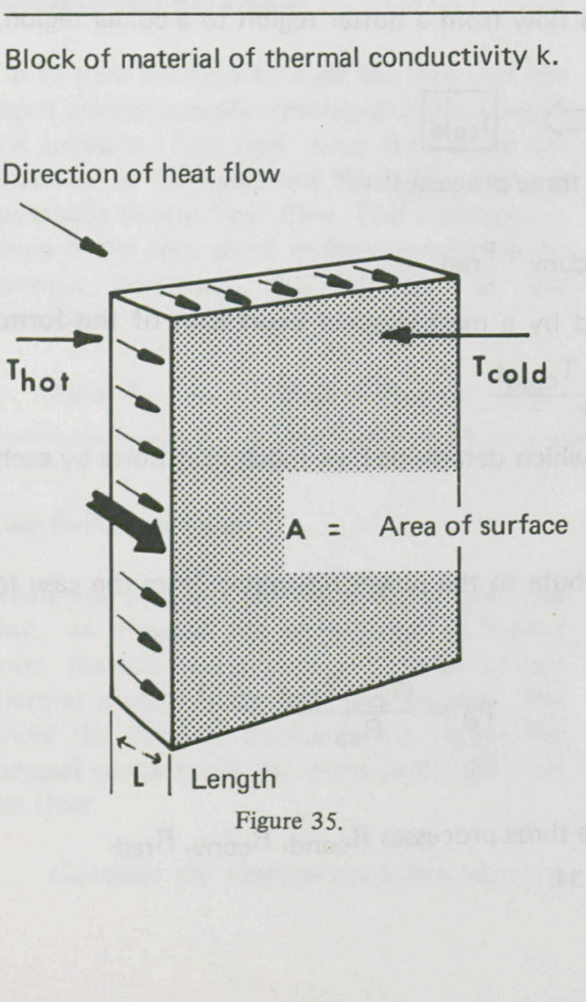


Figure 35.

Comparing Thermal Conductivities

You can see from Figure 36 that air is one of the poorest thermal conductors. A one-millimeter thickness of air has the same conductivity (for a given area) as a one-*meter* thickness of the average metal. Thus air is one of the best thermal *insulators*.

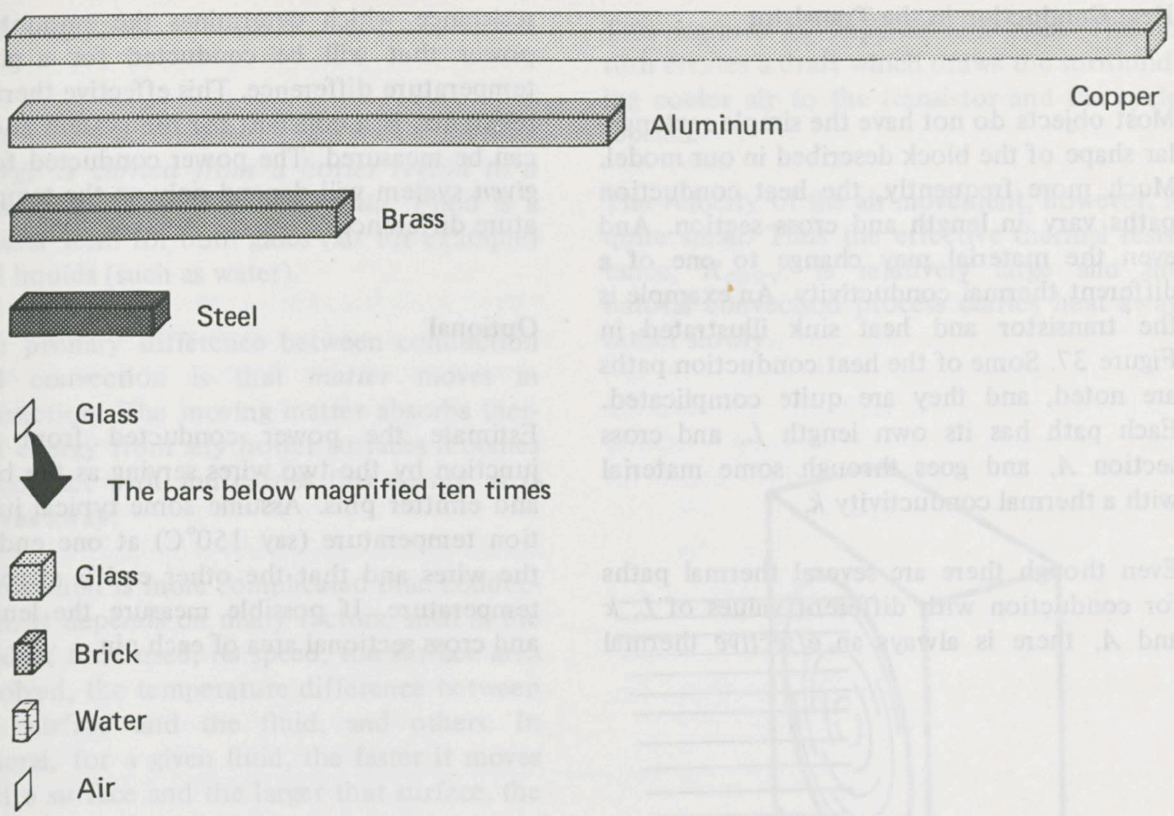


Figure 36. The bars above represent the equivalent lengths of each material which would give the same thermal resistance to heat flow by conduction.

Therefore, air is important when it surrounds a good conductor, such as the heat sink. Since its thermal conductivity is so small, very little heat is *conducted* away from the heat sink by the air. More heat is conducted away through the copper leads to the transistor. Even though their area is much smaller than the heat sink, the conductivity of copper is almost 10,000 times that of air.

If one relied only on conduction to remove the heat from the heat sink, it would be necessary to immerse it in water, for which the thermal conductivity is ten times that of air.

Table II.

Material	Thermal Conductivity k (W/cm°C)
Copper	3.85
Aluminum	2.01
Brass	1.09
Steel	.482
Glass	.01
Brick	.0063
Water	.0059
Air	.00069

Heat Conduction in the Transistor

Most objects do not have the simple rectangular shape of the block described in our model. Much more frequently, the heat conduction paths vary in length and cross section. And even the material may change to one of a different thermal conductivity. An example is the transistor and heat sink illustrated in Figure 37. Some of the heat conduction paths are noted, and they are quite complicated. Each path has its own length L, and cross section A, and goes through some material with a thermal conductivity k.

Even though there are several thermal paths for conduction with different values of L, k and A, there is always an *effective* thermal resistance which determines the amount of power that will be conducted for a given temperature difference. This effective thermal resistance is a constant for the system and it can be measured. The power conducted for a *given* system will depend only on the temperature difference.

Optional

Estimate the power conducted from the junction by the two wires serving as the base and emitter pins. Assume some typical junction temperature (say 150°C) at one end of the wires and that the other end is at room temperature. If possible measure the length and cross sectional area of each pin.

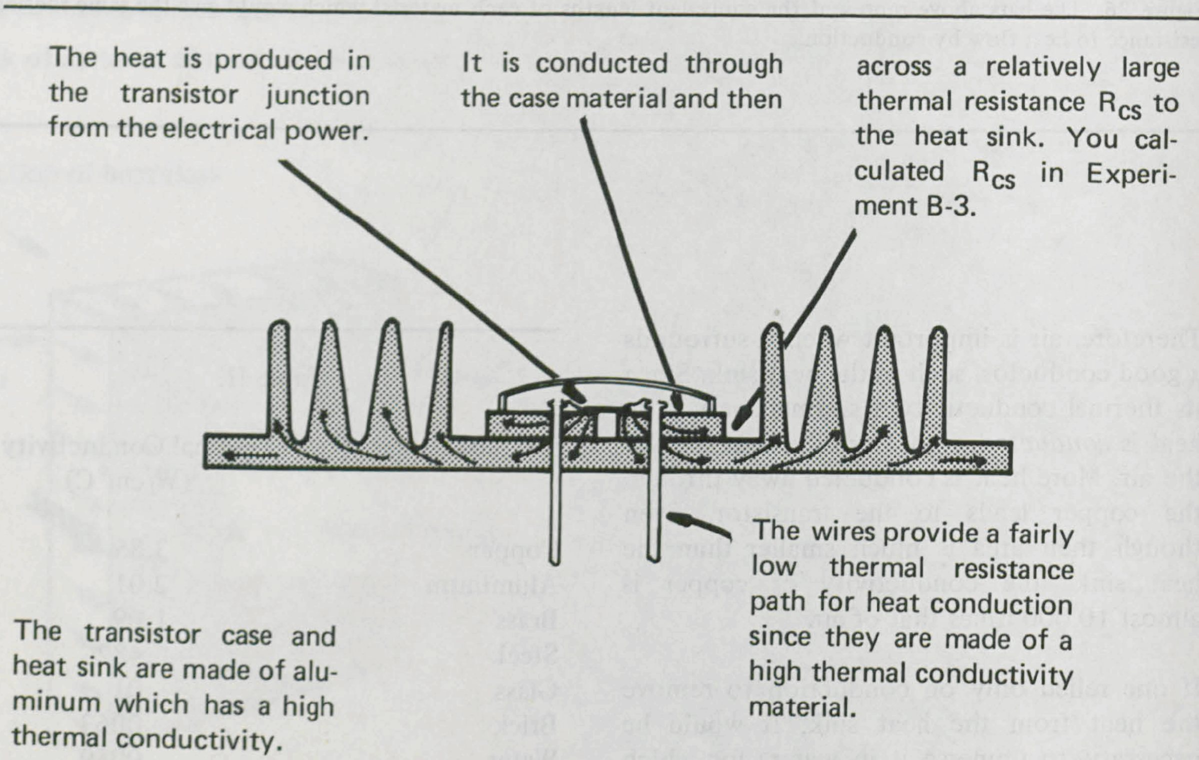


Figure 37.

CONVECTION

Convection is the process by which thermal energy is carried from a hotter region to a colder region by a moving fluid. Fluid is a general term for both gases (air for example) and liquids (such as water).

The primary difference between conduction and convection is that *matter* moves in convection. The moving matter absorbs thermal energy from any hotter surfaces it comes in contact with and carries this energy as it moves away.

Convection is more complicated than conduction. It depends on many factors, such as the kind of fluid used, its speed, the surface area involved, the temperature difference between the surface and the fluid, and others. In general, for a given fluid, the faster it moves past a surface and the larger that surface, the more power it convects away.

Natural Convection in the Transistor

Some convection occurs naturally when the transistor stands alone. Heat is conducted from the transistor case to the air around it.

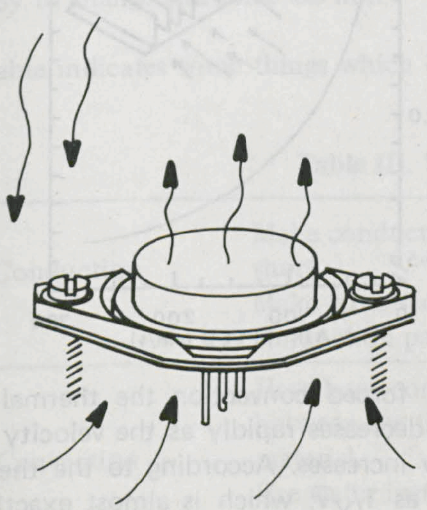


Figure 38.

This warmer air expands and rises. This in turn creates a draft which draws the surrounding cooler air to the transistor and the cycle repeats.

The velocity of the air movement, however, is quite small. Thus the effective thermal resistance, R_{conv}, is relatively large and the natural convection process carries heat away rather slowly.

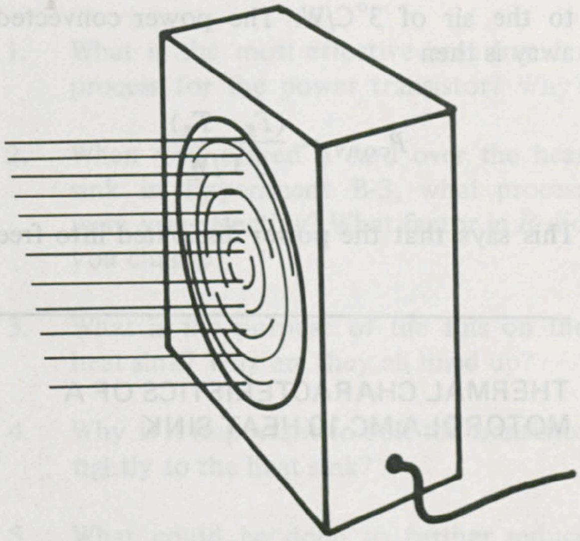


Figure 39.

Forced Convection in the Transistor

To decrease R_{conv} you first added a fan to increase the air velocity, and then a heat sink to increase the effective surface area of the transistor case. Each of these processes produced a reduction in the case-to-air thermal resistance. When you used the two together the resistance drop was dramatic. This, *forced convection,* combined with a large surface area, is an effective process for carrying away heat.

A more detailed discussion of convection appears in the optional material at the end of this section.

Convection and Heat Sink Design

Heat sinks are specifically designed to maximize heat flow. Since forced convection is such an effective heat transfer process, they are usually designed to make use of forced convection.

Figure 40 contains specification data for a heat sink similar to the one you used. The data shown can be readily understood in light of the discussion. For natural convection the heat sink has an effective thermal resistance to the air of 3°C/W. The power convected away is then

$$P_{\text{conv}} = \frac{(T_s - T_a)}{3°\text{C/W}}$$

This says that the power dissipated into free air is directly proportional to the difference in temperature between the sink (T_s) and the air (T_a). A plot of $(T_s - T_a)$ against P should be a straight line with a slope of 3°C/W. The experimental data follow this theoretical prediction at low temperatures but vary from it at higher temperatures.

Under forced convection the effective thermal resistance is proportional to $1/\sqrt{v}$, where v is the velocity of the convecting fluid. That is,

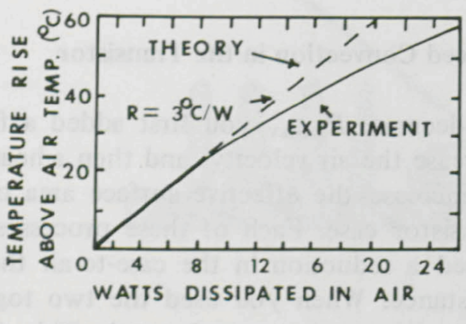
$$R_{\text{conv}} \propto \frac{1}{\sqrt{v}}$$

As the air velocity increases, R_{conv} decreases as the square root of the velocity. The curve of the experimental data follows this prediction quite closely.

THERMAL CHARACTERISTICS OF A MOTOROLA MC-10 HEAT SINK

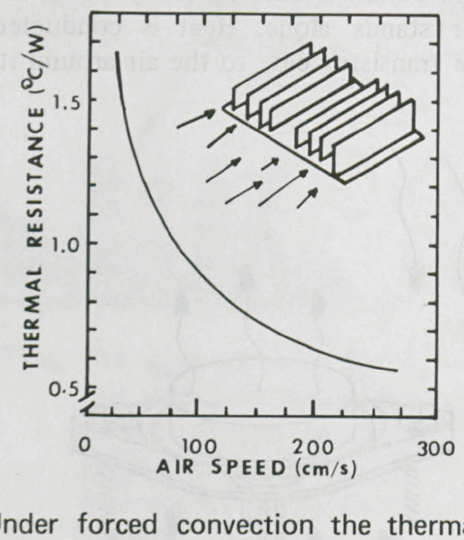
Material	Aluminum alloy
Finish	Black
Surface area	65 sq in
Thermal resistance	3 °C/W

Natural Convection



In natural convection the heat dissipated increases with the temperature difference between the sink and the air. The thermal resistance R (the slope of the curve) decreases slightly as T increases because natural convection and radiation become more efficient at higher transistor temperatures.

Forced Convection



Under forced convection the thermal resistance decreases rapidly as the velocity of air flow v increases. According to the theory R varies as $1/\sqrt{v}$, which is almost exactly the equation of the curve shown.

Permission to use courtesy of Motorola Semiconductor Products, Inc.

Figure 40.

RADIATION

Heat radiation is the process by which thermal energy is transferred from one object to another without having any matter between them.

Radiation differs from both conduction and convection in that no material, either solid or fluid, is required to carry the thermal energy. Heat is radiated by an object in the same way that visible light is radiated from the filament of a light bulb. Heat radiation is simply in a different energy range where our eyes are not sensitive. Heat radiation is also called *infrared radiation.*

Since radiation carries only a small amount of heat from the transistor we will not discuss it in detail. However a brief analysis of radiation as it relates to the power transistor may be found at the end of this section.

INCREASING THE RATE OF HEAT TRANSFER

You now have some knowledge of what factors influence the *rate* of heat transfer for each kind of process. Some of these factors are easy to change and some are not.

The table indicates some things which can be done to reduce the effective thermal resistance for each process, and thus increase the heat flow for a given temperature difference.

APPLYING THE RESULTS TO YOUR DATA

You are now in a position to better understand the four heat transfer experiments you performed. See if you can answer the following questions.

1. What is the most effective heat transfer process for the power transistor? Why?
2. When you placed a card over the heat sink in Experiment B-3, what process were you affecting? What factor in R did you change?
3. What is the purpose of the fins on the heat sink? Why are they all lined up?
4. Why is it important to bolt the transistor tightly to the heat sink?
5. What could be done to further reduce the thermal resistance of each of the processes?
6. Why do you think each of your recommendations in step 5 are not commonly done?

Table III. Ways to Increase Heat Flow

Conduction	Make conduction paths (L) short. Make cross-sectional area of conduction paths (A) large.	Choose materials of high thermal conductivity (k). Have good thermal contact between adjoining parts.
Convection	Have large contact area (A) between the fluid and the material. Use water instead of air as the fluid.	Provide for good circulation of the fluid. Increase the fluid velocity.
Radiation	Have a large surface area (A). Have a high-temperature object or cold surroundings.	Choose materials which are good radiators. Paint the surface black.

OTHER APPLICATIONS OF HEAT-TRANSFER PHYSICS

The last few pages have described the three heat-transfer processes primarily as they apply to the power transistor. The physics of heat transfer, of course, has applications beyond this specific case. You could have performed similar experiments on other systems with similar results.

One important difference you would find, however, is that the process of heat transfer varies from one situation to another. That is, more than one process may be at work in a single case, but one of them is usually more important. The steps necessary to change the rate of heat flow depend on which process dominates that particular situation.

In the following we discuss briefly a number of situations in which each process dominates.

Conduction

Metals are the best thermal conductors as well as being the best electrical conductors. Thus, heat flow by conduction is most efficient when metals provide a path for the heat. Water is a fairly good thermal conductor, as are most liquids, but it is not nearly so good as most metals. The rather poor thermal conductivity of glass makes it easy to melt a glass rod while holding it without burning your fingers. This could not be done with a metal rod.

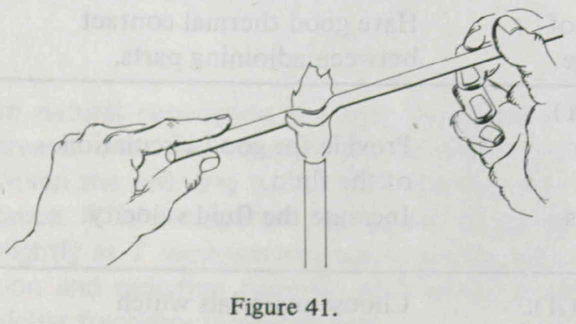


Figure 41.

One of the best thermal *insulators* is air. Few other substances have so low a thermal conductivity. Because of this, the warmest coats are those which keep a large amount of still air "trapped" in them, thus keeping the wearer well insulated. (It is important that the air be kept still since that keeps convection from occurring.)

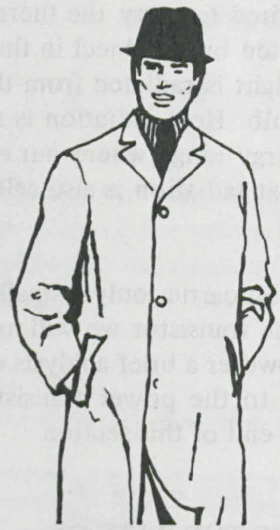


Figure 42.

The still air between a regular window and a storm window is the main reason that storm windows are useful in keeping a house warm.

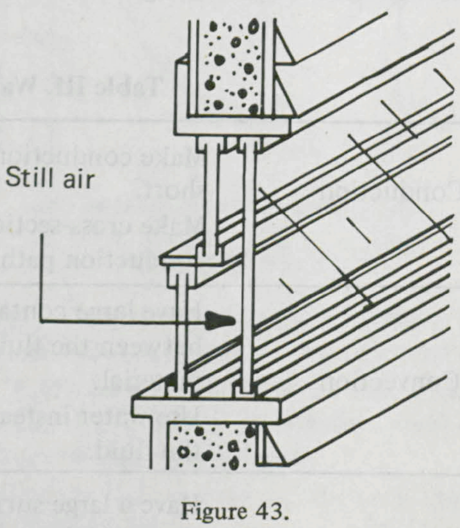


Figure 43.

Convection

Wherever there is a moving fluid (air, water, etc.), convective heating and cooling occur. Water is a better convective coolant than air because of its higher thermal conductivity and higher *specific heat.* But, as you saw in the experiments, air can be quite effective. Both substances are used in house heating systems.

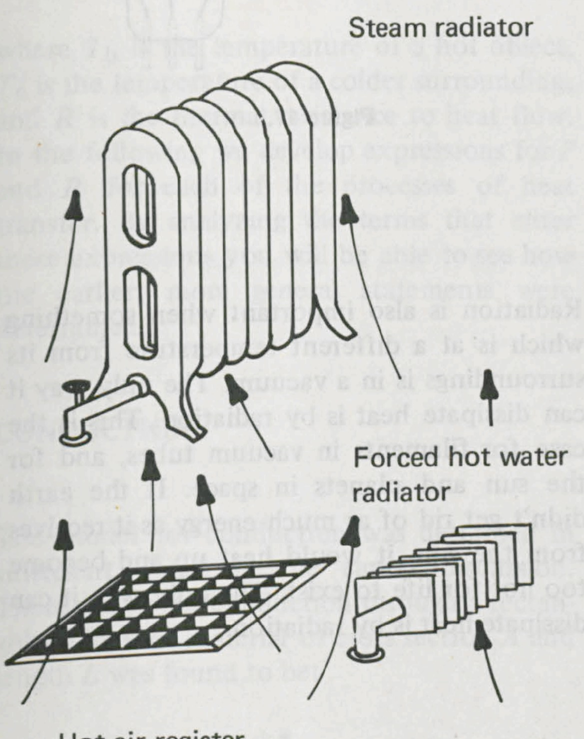


Figure 44.

In a hot air system, air is heated and then blown into the rooms of the house. (In older "gravity flow" heating systems, there is no blower, and the warm air rises from the furnace by natural convection.) When water is used, the water is pumped through metal pipes which have high thermal conductivity. The thermal energy from the water is conducted through the pipe walls and into metal fins in the room radiator. From there the natural convection currents in the room carry away the heat. The "radiator" is really a "convector."

Convection is particularly important when evaporation or condensation takes place. When the perspiration on our skin evaporates, it uses a large amount of energy in changing from a liquid (water) to a gas (water vapor). The energy taken away in this process leaves the body cooler.

A wind greatly increases the evaporation rate. This is why a breeze is so welcome on a hot summer day. The convective cooling done by the air is made much more effective by the evaporation of water.

Fireplaces would not work if it were not for convection. The fire heats the air, which rises, creating a *draft.* The draft sucks in more cooler air and also carries away the smoke. The heating of the room however is primarily by radiation from the flame and the hot fireplace chamber, because most of the convected heat goes out the chimney.

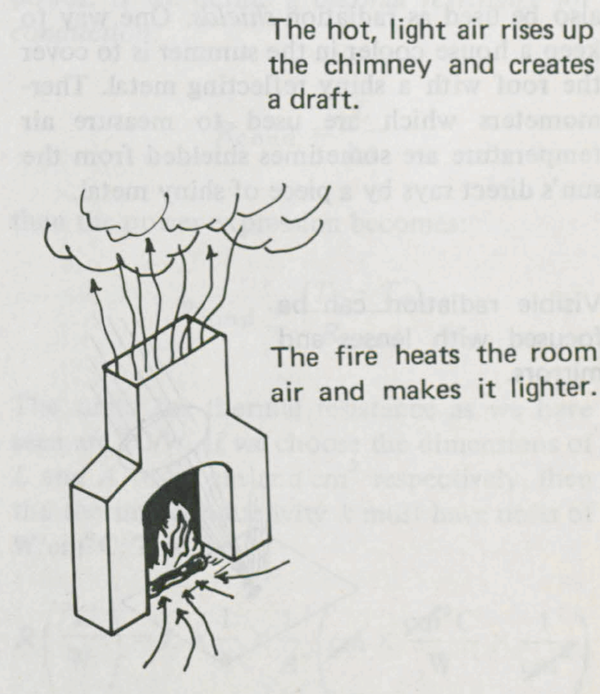


Figure 45.

Radiation

Heat transfer by radiation dominates whenever a body is glowing visibly. The earth receives most of its energy by radiation from one such glowing body, the sun. Bodies give off visible light only when their temperature gets above about 500°C. The amount of energy radiated in a given time increases as the fourth power of temperature. Thus, as the temperature increases the radiated power increases rapidly.

Electrical heaters are often made for heating rooms, ovens, or toasters by dissipating enough electrical power in a piece of metal to make it glow "red hot." Much of the heat thus generated is transferred to the surroundings by radiation.

Reflectors and lenses can be used to redirect or focus radiant energy in the same way as they focus visible light. Many toasters and room heaters have reflectors to direct the energy in the desired direction. Reflectors can also be used as radiation *shields.* One way to keep a house cooler in the summer is to cover the roof with a shiny reflecting metal. Thermometers which are used to measure air temperature are sometimes shielded from the sun's direct rays by a piece of shiny metal.

Visible radiation can be focused with lenses and mirrors.

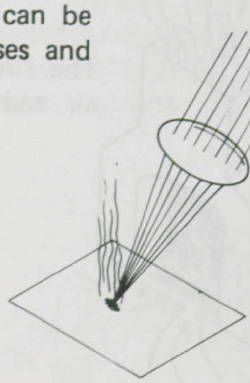


Figure 46.

A filament of a vacuum tube is in a vacuum. The glass walls of the tube heat up primarily by radiation.

Figure 47.

Radiation is also important when something which is at a different temperature from its surroundings is in a vacuum. The only way it can dissipate heat is by radiation. This is the case for filaments in vacuum tubes, and for the sun and planets in space. If the earth didn't get rid of as much energy as it receives from the sun, it would heat up and become too hot for life to exist. The only way it can dissipate heat is by radiation.

Infrared radiation can be focused with reflectors.

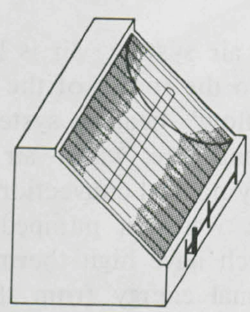


Figure 48.

THE MATHEMATICAL BASIS OF HEAT TRANSFER (OPTIONAL)

In this optional section we want to give our discussion of heat transfer a more mathematical foundation. Earlier we said that the power transferred by each of the heat transfer processes could be expressed in the form:

$$P = \frac{(T_h - T_c)}{R}$$

where T_h is the temperature of a hot object, T_c is the temperature of a colder surroundings and R is the thermal resistance to heat flow. In the following we develop expressions for P and R for each of the processes of heat transfer. By analyzing the terms that enter these expressions you will be able to see how the earlier, more general statements were determined.

CONDUCTION

The model for conduction was described in sufficient detail in the earlier discussion. There the power conduction through a rectangular block of material of cross section A and length L was found to be:

$$P_{cond} = \frac{kA}{L}\,(T_h - T_c)$$

where k is the *thermal conductivity* of the material.

P_{cond} is large for materials of high thermal conductivity, large cross sectional area and when the temperature difference is large. It is small, however, if the thermal path, L, is long.

Thermal Resistance for Conduction

The expression for conducted power has the same form as the relation for dissipated

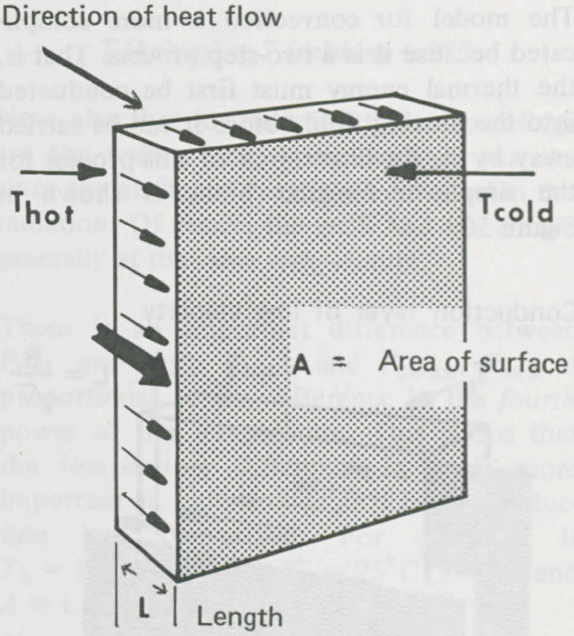


Figure 49.

power. If we define a *thermal resistance for conduction:*

$$R_{cond} = \frac{L}{kA}$$

then the power expression becomes:

$$P_{cond} = \frac{(T_h - T_c)}{R_{cond}}$$

The units for thermal resistance as we have seen are °C/W. If we choose the dimensions of L and A to be cm and cm^2 respectively, then the thermal conductivity k must have units of W/cm°C. That is:

$$R\left(\frac{°\mathrm{C}}{\mathrm{W}}\right) = L \times \frac{1}{k} \times \frac{1}{A}\left(\cancel{\mathrm{cm}} \times \frac{\cancel{\mathrm{cm}}\,°\mathrm{C}}{\mathrm{W}} \times \frac{1}{\cancel{\mathrm{cm}^2}}\right)$$

$$= \frac{L}{kA}\ (°\mathrm{C/W})$$

CONVECTION

The model for convection is more complicated because it is a two-step process. That is, the thermal energy must first be conducted into the moving fluid before it can be carried away by it. An illustration of this process for the simple rectangular block is shown in Figure 50.

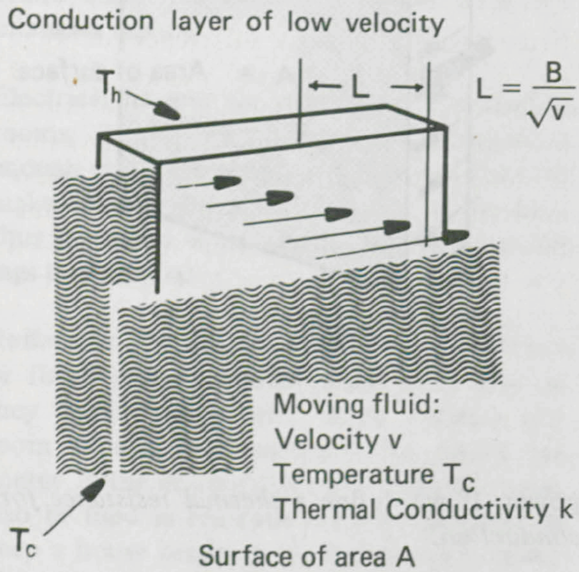


Figure 50.

The first step in getting P_{conv} is to get an expression for the thermal power conducted from the block's surface into a fluid of thermal conductivity k. From our discussion of conduction that will be:

$$P_{cond} = \frac{kA}{L}(T_h - T_c)$$

Now the question is, how far must the heat be conducted into the fluid before it will be carried away? The thickness of this so called "conduction layer" depends on a lot of properties of the fluid, its specific heat, its "viscosity" and its velocity. Of these, velocity is the most important since it is what we can control most easily in practical applications. In terms of velocity the thickness of the conduction layer is:

$$L = \frac{B}{\sqrt{v}}$$

where v is the velocity of the fluid *outside* the conduction layer and B includes the effects of all of the other properties. Putting this into the conduction expression gives the *thermal power convected:*

$$P_{conv} = \frac{kA\sqrt{v}}{B}(T_h - T_c)$$

P_{conv} is large when the fluid has a high thermal conductivity k, is moving with a large velocity v past a surface of large area A and is much colder than the surface.

Thermal Resistance for Convection

The expression for thermal power transferred by convection can be written like that for P_{cond},

$$P_{conv} = \frac{(T_h - T_c)}{R_{conv}}$$

if we define a *thermal resistance for convection.*

$$R_{conv} = \frac{B}{kA\sqrt{v}}$$

Since there are many unknown factors hidden in the constant B, R_{conv} is difficult to calculate. But it can be determined experimentally.

To maximize P_{conv} one must reduce R_{conv}. That requires a large surface area A and a high fluid velocity v. For the power transistor the heat sink increases the effective surface area of the case, and the fan produces a high air velocity. If the cooling problems are particularly serious, one could use a fluid of higher thermal conductivity. For example, water has a higher thermal conductivity than does air.

RADIATION

We will not develop a detailed model for radiation for two reasons. First, in most thermal systems heat transfer by radiation is small compared to transfer by conduction and convection. Second, the subject is too complicated to cover in detail here. It is covered more thoroughly in the *Incandescent Lamp* module.

Since radiation is one of the three primary heat transfer processes, however, we will indicate the results of a complete treatment so that you can see what factors affect the thermal resistance for radiation. Again we will examine the same rectangular block of material as shown in Figure 51.

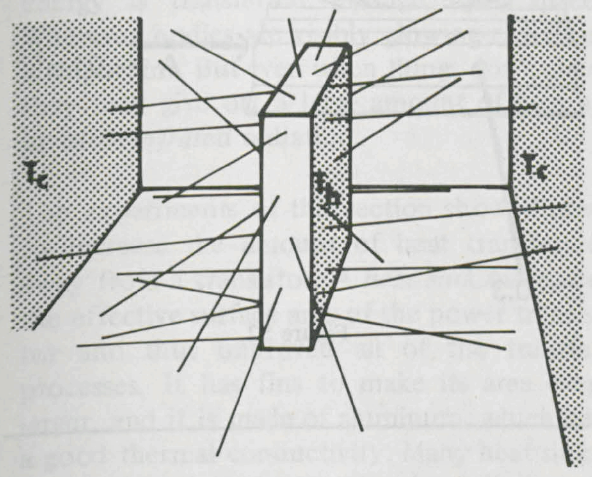


Figure 51. Object of surface area A and emissivity ϵ.

The net thermal power radiated from a block of total surface area A at temperature T_h, to its surroundings at a colder temperature T_c, is:

$$P_{rad} = \epsilon \sigma A (T_h{}^4 - T_c{}^4)$$

The constant ϵ (Greek letter *epsilon*) is called the *emissivity* of the object and its size depends on what the object is made of. The constant σ (Greek letter *sigma*) is a constant of nature called the *Stefan-Boltzmann constant*. The *temperature* of the surroundings must be measured *in* kelvins (K):

$$T\ (\text{kelvin}) = T\ (\text{celsius}) + 273$$

Note also that for radiation the *surroundings* are the walls of the room and *not the air*, since the air is not very much involved in the radiation. Of course the walls and the air are generally at the same temperature.

There is an important difference between P_{rad} and both P_{conv} and P_{cond}. P_{rad} is proportional to the difference in the *fourth* power of the temperature. This means that the temperature difference is much more important in radiation than it is for conduction and convection. For example, if $T_h = 125°C$ (398 K), $T_c = 25°C$ (298 K) and $A = 1\ cm^2$ then:

$$T_h - T_c = 100\ K$$

but,

$$(T_h{}^4 - T_c{}^4) = (398^4 - 298^4)\ K^4$$

$$= 1.7 \times 10^{10}\ K^4$$

Since the value of σ is

$$\sigma = 5.7 \times 10^{-8}\ \frac{W}{m^2 K^4}$$

and the emissivity is a number between zero and one, these factors largely offset each other, except for very large temperature differences.

Thermal Resistance for Radiation

Since the power transferred by radiation does not have the same temperature dependence as in conduction and convection, we must be careful how we define thermal resistance for radiation. It *will not* be the same as for conduction and convection.

We can write the power as:

$$P_{\mathrm{rad}} = \frac{(T_{\mathrm{h}}^{\,4} - T_{\mathrm{c}}^{\,4})}{R'_{\mathrm{rad}}}$$

and define the *thermal resistance of radiation* as:

$$R'_{\mathrm{rad}} = \frac{1}{\epsilon\,\sigma\,A}$$

The prime means that R'_{rad} has different units than R_{cond} and R_{conv}. R'_{rad} has units of K^4/W rather than °C/W (or K/W).

We can look at R'_{rad} to see what it depends on and what factors we can change to decrease it. First, it depends on σ. But σ is a constant of nature which cannot be changed. Next it depends on the area A as do the other thermal resistances. If you increase A you decrease R'_{rad} and increase heat transfer by radiation.

Finally R'_{rad} depends on the emissivity ϵ. For different materials ϵ varies from 0 to 1, with a *perfect radiator* having an emissivity of 1. A perfect radiator is also called a *black body* since it appears black. The heat sink and transistor case are made of aluminum, which has an emissivity of about 0.3.

Radiation in the Transistor

We said that radiation does little to transfer heat from the power transistor. The reason is that the radiated power depends on the fourth power of the temperature. Since σ is such a small number (10^{-8} W/K^4 m^2), $(T_{\mathrm{h}}^{\,4} - T_{\mathrm{c}}^{\,4})$ must be large in order for P_{rad} to be large.

But the whole point is to keep the transistor temperature (T_{h}) down, and as close to the surrounding temperature (T_{c}) as possible. If we achieve this, then we necessarily make P_{rad} small.

An estimate of P_{rad} for the *maximum* tolerable case temperature of 200°C is given in Figure 49. As can be seen, if ϵ were its maximum value of 1, P_{rad} would be about 20 watts.

$$T_{\mathrm{c}} = 25 + 273 = 298\ \mathrm{K}$$

$$T_{\mathrm{h}} = 200 + 273 = 473\ \mathrm{K}$$

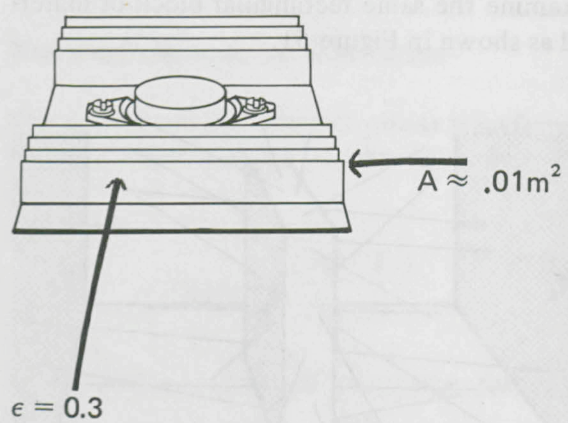


Figure 52.

$$P_{\mathrm{rad}} = \epsilon\sigma A\,(T_{\mathrm{h}}^{\,4} - T_{\mathrm{c}}^{\,4})$$

$$= 0.3 \times 5.7 \times 10^{-8}\ \frac{\mathrm{W}}{\mathrm{m}^2\,\mathrm{K}^4} \times .01\mathrm{m}^2 \times$$

$$[(473)^4 - (298)^4]\ \mathrm{K}^4$$

$$= 1.7 \times 10^{-10} \times (5 - 0.77) \times 10^{10}\ \mathrm{W}$$

$$= 1.7 \times 10^{-10} \times (4.2 \times 10^{10})\ \mathrm{W}$$

$$\approx 7\ \mathrm{W}$$

SUMMARY

The three main heat transfer processes are *conduction, convection,* and *radiation.*

Conduction is the process in which thermal energy is transferred through a body, but no mass is transferred. Conduction is most important when the fluid velocity is high. Convection depends on conduction to get the heat from the solid object into the fluid.

Convection is the process in which thermal energy is carried away by a moving fluid, such as air or water. Nearly everywhere that a fluid flows, convection occurs. It is particularly important when the fluid velocity is high.

Radiation is the process in which thermal energy is transferred through open space. Wherever bodies are visibly glowing radiation is important. But even when things don't glow they may give off a large amount of heat as invisible *infrared* radiation.

The experiments of this section showed how to increase the amount of heat transferred away from a transistor. A *heat sink* increased the effective surface area of the power transistor and thus improved all of the transfer processes. It has fins to make its area even larger, and it is made of aluminum, which has a good thermal conductivity. Many heat sinks are black to increase heat loss by radiation. A *fan* makes the air move faster past the heat sink, thus increasing the convective cooling.

Conservation of energy states the fact that energy changes form but doesn't disappear. This makes it possible to describe mathematically the behavior of a thermal system. For a power transistor, this leads to the equation:

$$\textit{power input} = \textit{power dissipated to surroundings} + \textit{power to heat the transistor}$$

or

$$P_i = P_d + P_h$$

For the steady state, $P_h = 0$ so that $P_i = P_d$.

The *input power* is:

$$P_i = VI$$

The *dissipated power* is:

$$P_d = \frac{(T_{case} - T_{air})}{R_{ca}}$$

Substituting these gives the energy conservation equation for the steady state:

$$VI = \frac{(T_{case} - T_{air})}{R_{ca}}$$

When a steady state exists, this equation gives us an expression for determining experimentally the *thermal resistance:*

$$R_{ca} = \frac{(T_c - T_a)}{VI}$$

Then using the thermal resistance we have found the final case temperature for any power input is:

$$T_f = T_a + R_{ca}(VI)$$

Another result of the experiments was to show that the thermal resistance does not depend on temperature. Thus it can be used to predict the maximum safe operating power using the Power Temperature Derating Curve.

QUESTIONS

1. There are other kinds of resistances that are useful in applying physics to various situations. We have discussed *electrical* resistance, which enters into Ohm's Law:

$$I = \frac{V}{R}$$

In this equation, the electrical current, I, is analogous to the "heat current," P_d, and the potential difference, V, is analogous to the temperature difference $(T_h - T_c)$.

Another kind of resistance (fluid resistance) is used to describe the flow of liquids in tubes,

$$v = \frac{P_1 - P_2}{R_f}$$

What this equation says is that the velocity v of a fluid in a pipe is a constant times the difference in pressure between the two ends of the pipe.

a. Using this, what is R_f for a pipe which requires a pressure *difference* of 200 N/m^2 to maintain a velocity of 15 m/s?

b. What do you think would happen to R_f if the pipe were twice as long? If the pipe had twice the diameter?

2. Suppose the air temperature was 5°C near a river whose temperature was also 5°C. In the air on this day, the temperature of a brave-hearted person's skin was maintained at 30°C by the heat generated by the chemical reactions in his body. Further suppose that this person decided to go swimming.

   a. If the heat he generates stays constant, what happens to his skin temperature?

   b. If the thermal resistance from his skin to the surroundings changes by a factor of 10 when he enters the water (which way?), what would his final skin temperature be?

   c. When this brave soul gets out of the water, will his thermal resistance to the air be the same as before? If not, what has changed? Would his skin temperature be higher or lower than it was before he went swimming?

   d. What heat transfer processes are most important in each of the above situations?

3. Describe all the ways you can think of that the basic heat transfer processes operate when a light bulb heats the air in a room. (Modern incandescent lamps contain some gas.)

Problem

1. What is the thermal resistance of a square window pane (length of side = 0.75 m), which has a thickness of 0.2 cm? How much power is being *conducted* through it when the inside temperature is 25°C and the outside is −5°C? −5°C?

SECTION C

Transient Thermal Behavior

The word *transient* means "temporary," or "quickly passing." In common speech, a hotel guest who stays for only a few days is called a "transient" guest.

In physics, a change that takes place between two long-lasting or *steady-state* conditions is called a *transient change.* For example, in Section A the power transistor was initially at room temperature. Thus it had a steady-state temperature of about 21°C. When you turned on the power its temperature increased; this was a period of transient temperature change. Finally it leveled off at a new higher temperature which became its new steady-state temperature.

EXAMPLES OF THERMAL TRANSIENTS

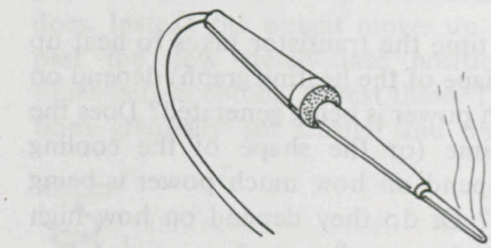
Thermal transients are probably the most frequent types of transient behavior that we encounter. Figure 53 shows only a few examples. You can probably think of others.

In these and other examples, the most important concern is generally *how long* does it take for the thermal transient to be over. For example, how long does it take for coffee to cool off so you can drink it, or until it is too cold to drink? How long does it take before the engine warms up and the car is ready to drive? And so on.

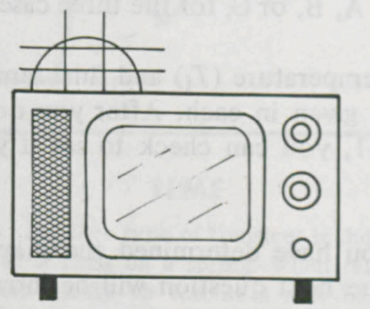
"How long" refers to the *time* that it takes for the temperature to change from one value to another. This time can be described by various names: *time constant, response time, rise time,* or *decay time* depending on the nature of the transient. The purpose of Section C is to understand these transients and learn about the time it takes them to occur.

Examples of thermal transients.

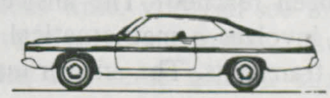
Cooling of a cup of coffee.



Heating of a soldering iron.



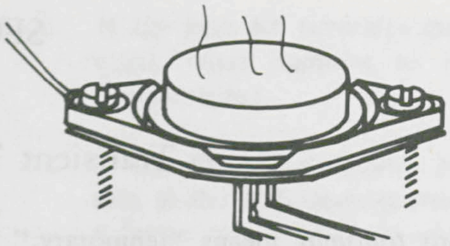
Warming up of a TV.



Warming up of an automobile engine.

Figure 53.

DESCRIBING TRANSIENT BEHAVIOR



To analyze the character of transient temperature change and to determine the times involved, it will be necessary to have graphs of the temperature of an object as it changes with time. In the experiments of this section you will make such graphs as in Figure 54, for the power transistor as it heats up when the power is switched on, and as it cools when the power is switched off.

When the power transistor undergoes transient temperature change, what shape will the temperature vs. time graph take in warming, in cooling, and at different power levels?

Some questions you might ask are:

What form will such graphs take? Will they be straight lines? Concave up? Concave down?

Will they be the same for warming as for cooling?

Does the time the transistor takes to heat up (or the shape of the heating graph) depend on how much power is being generated? Does the cooling time (or the shape of the cooling graph) depend on how much power is being generated? Or do they depend on how high the temperature goes?

In the illustrations in Figure 54, mark your guesses, A, B, or C, for the three cases shown.

Initial temperature (T_i) and final temperature (T_f) are given in each. After you do Experiment C-1, you can check to see if you were right.

When you have determined the shape of the curve, the next question will be, how long is the transient? For example, suppose the curve approaches the final temperature very slowly.

At what time can you say the final temperature has been reached? The answer to these questions involves a mathematical treatment of simple transients. The answer may surprise you.

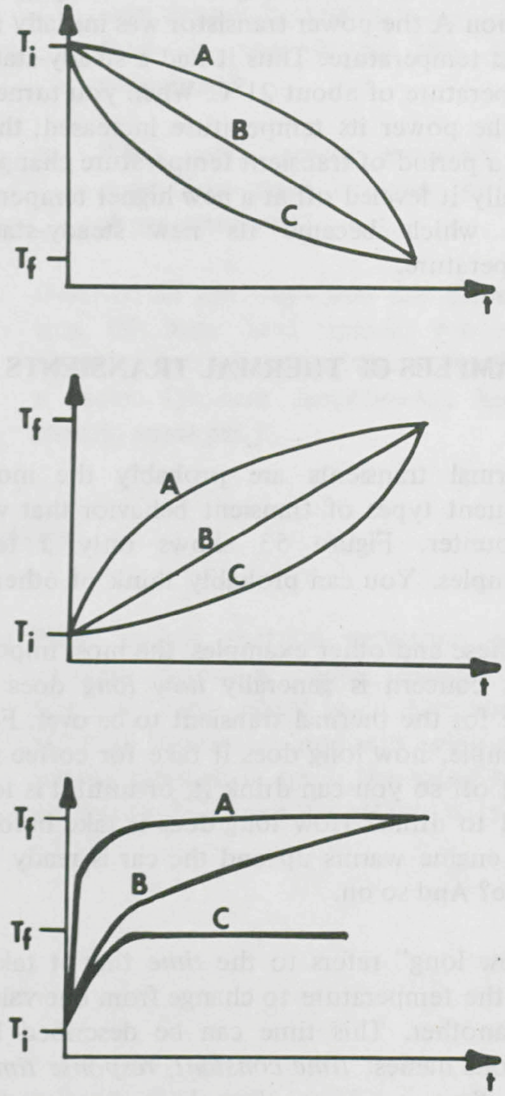


Figure 54.

OTHER TYPES OF TRANSIENTS

Other kinds of transient behavior occur in nature besides those involved in the heating and cooling of objects. Transients occur when a physical system cannot respond immediately to a change in the external factors which affect it. Mechanical systems do not respond immediately to a change in the applied force because of the property we call *inertia,* or mass. Electrical systems do not respond immediately to changes in applied voltage because of an analogous property called *reactance.* Thermal systems do not respond immediately to changes in external temperature because of a property which we may call *thermal inertia.*

One example of transient behavior similar to that of thermal systems is found in the way in which the current in a dc circuit containing a coil of wire changes in time. It turns out that when the circuit is "turned on," the current changes from its original steady-state value of zero to a new steady-state value i_f in a manner identical to the way in which the temperature of an object changes when the object is heated. Mathematically, the two processes are identical.

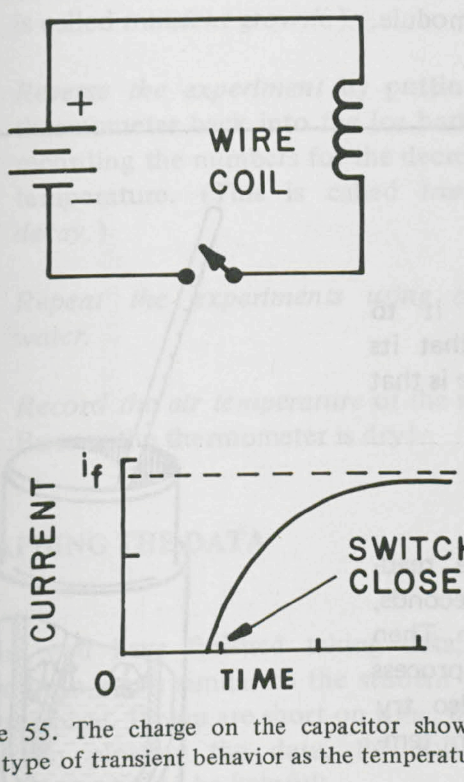


Figure 55. The charge on the capacitor shows the same type of transient behavior as the temperature of a heating room.

TRANSIENT OSCILLATIONS

Another type of transient behavior occurs in both electrical and mechanical systems. A weight hung on a spring provides one example. If the spring is stretched and held (original steady-state position), then released, it does not proceed to a new steady-state position in the same way as a thermal system does. Instead the weight moves up and down past the new steady-state position several times before coming to rest there. The oscillations gradually get smaller and finally stop.

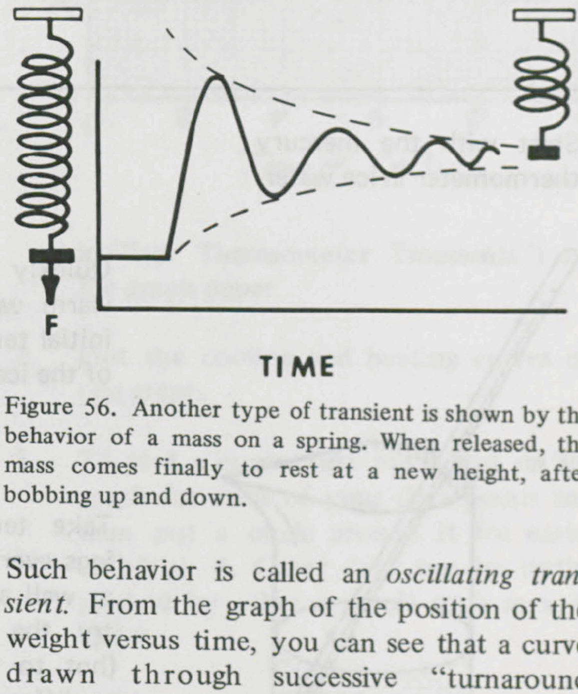


Figure 56. Another type of transient is shown by the behavior of a mass on a spring. When released, the mass comes finally to rest at a new height, after bobbing up and down.

Such behavior is called an *oscillating transient.* From the graph of the position of the weight versus time, you can see that a curve drawn through successive "turnaround points" has the same general shape as do thermal transients.

EXPERIMENT C-1. Transients in a Mercury Thermometer

The heating and cooling of the mercury thermometer demonstrates most of the principles of transients quite well. The object of these experiments is to look at thermometer transients in detail. (Note: In this experiment, as well as in the one on the power transistor, there are a number of things to be done in a short period of time. Because of this, you will probably find it helpful to work with another person.)

Preparation

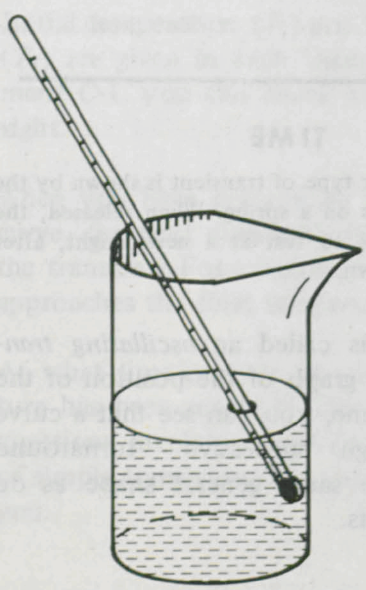
Fill a beaker with warm tap water (the particular temperature isn't important).

Fill the insulated container used for the thermocouple reference junction with cold water. This will provide a convenient cold-temperature bath.

t (sec.)	t(°C)	T(°C)	t(°C)
0			
3			
6			
9			
⋮			

Prepare a data table like the one shown. Use the space provided on the data page. The entries in the time column should be about every three seconds and extend to time greater than the response time of your thermometer as determined in Section A. Remove the data pages for Section C from the back of the module.

Start with the mercury thermometer in ice water.



Quickly transfer it to warm water so that its initial temperature is that of the ice water.

Take temperature readings every three seconds, as well as you can. Then try the reverse process (hot to cold). Also try a different water temperature.

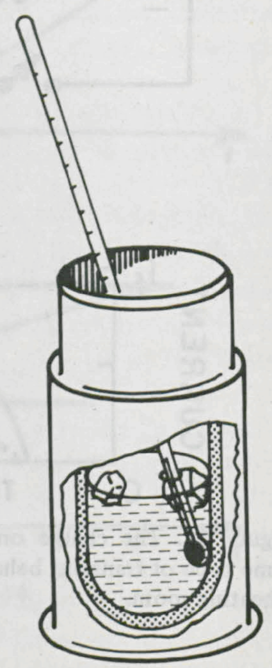


Figure 57.

Procedure

1. *Put the mercury thermometer* in the cold-water bath, and wait until it comes to the cold-water temperature. When the temperature becomes constant, record it as the $t = 0$ s temperature.

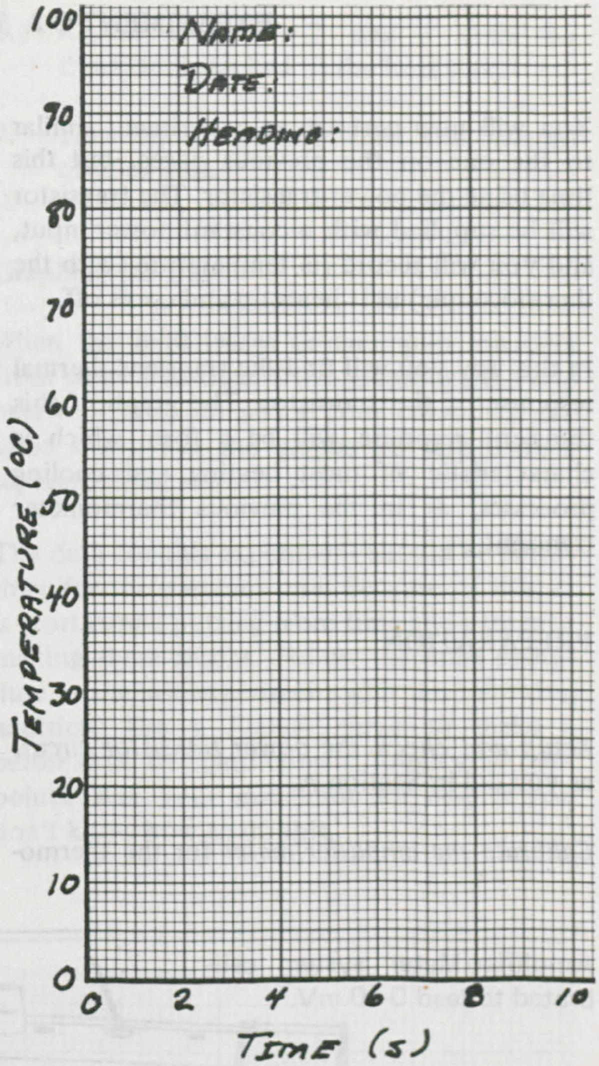
2. *Transfer the thermometer* quickly to the warm water, so that its temperature doesn't go up very much before it gets there.

3. *Start counting seconds immediately.* Take temperature readings every three seconds until the temperature has stopped changing. The person who is counting can call out readings to the other person who records them in the table. Your data will only be approximate, but do the best you can. You might find it helpful to practice a couple of times first. (This process of increasing is called *transient growth.*)

4. *Reverse the experiment* by putting the thermometer back into the ice bath and recording the numbers for the decreasing temperature. (This is called *transient decay.*)

5. *Repeat the experiments using cooler water.*

6. *Record the air temperature* of the room. Be sure the thermometer is dry!



GRAPHING THE DATA

When you have finished taking data, plot them on a graph similar to the student graph on this page. If you are short on time, do this later. In plotting the data, the following suggestions should be helpful:

1. Put your name, the date, and an adequate heading (for example "Mercury-in-Glass Thermometer Transients") on the graph paper.

2. Plot the cooling and heating curves on one graph.

3. To plot a curve, first put a dot on the graph for each of your data points and then put a circle around it for easier visibility, ⊙. Other data can be distinguished by other symbols such as x, △, and ⊡.

4. Connect each set of data points with a smooth curve. Some points may not quite be on this curve, but about as many points should be below the curve as above it.

EXPERIMENT C-2. Transients in a Transistor

You will now perform an experiment similar to the one on the previous pages, but this time using the power transistor. The transistor will be supplied with a constant power input, and you will record its temperature (with the thermocouple) as it heats up and cools off.

In this way you will find the transient thermal response of the transistor. The graph of this transient response will be a form which is characteristic of most heating and cooling processes, as in the previous thermometer transient.

PREPARATION

Setup and check the power transistor circuit as you did in Section A.

Calibrate the amplifier/meter for the thermo-

t (min)	meter reading (mV)	t(°C)	meter reading (mV)	t(°C)
0				
0.25				
0.5				

couple. Use a cold-water bath, and make sure the thermocouple system is working properly (check 0°C and room temperature).

Attach the thermocouple to the transistor as in Section A.

Prepare a data table like the one shown. Use the space provided on the data page. During the first minute, you should take data at 15 s intervals. As the temperature increases more slowly, take data at longer intervals.

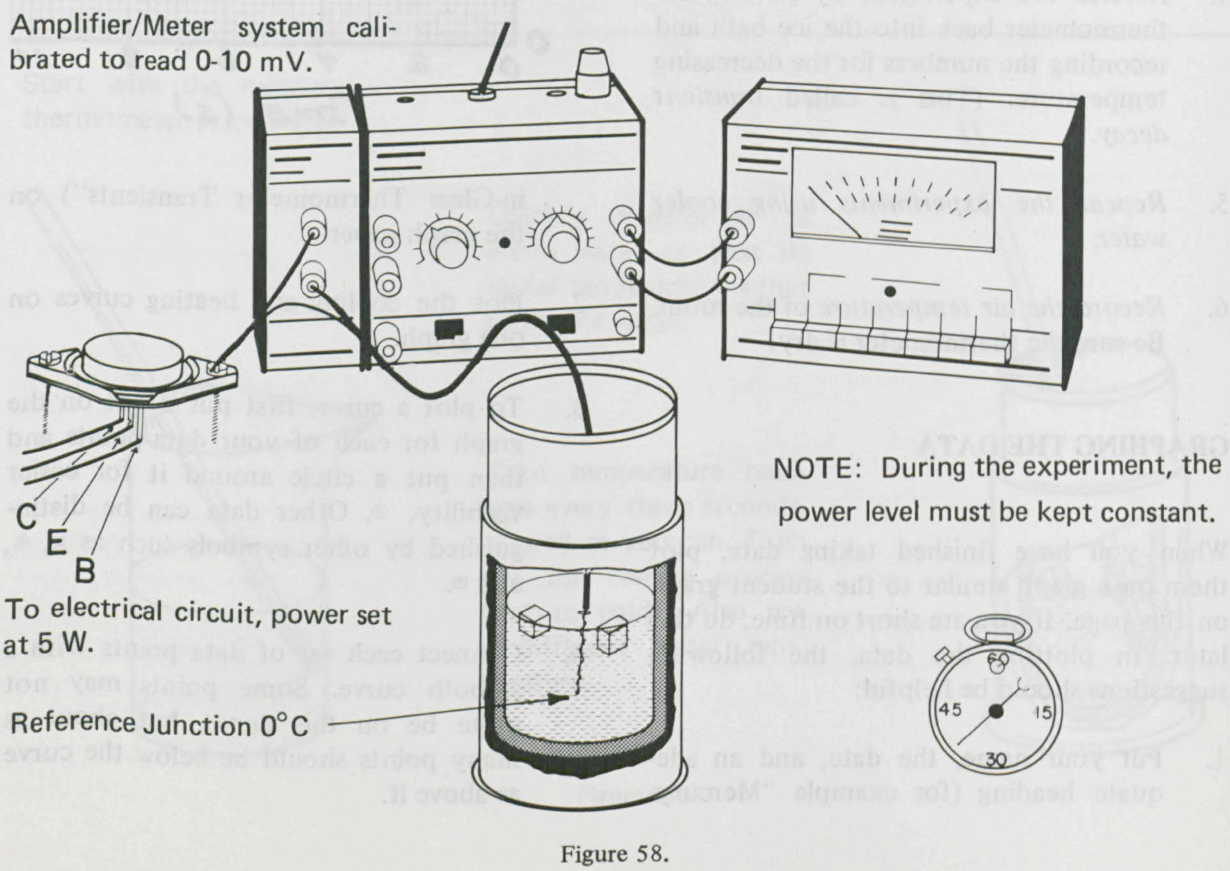


Figure 58.

PROCEDURE

1. *Quickly set the transistor power* to 5 W; then, without changing the current, switch off the power supply.

2. *Let the transistor cool* back to room temperature. A fan or cold wet cloth may speed the process.

3. *Switch on the power supply and stop-watch* and start taking data. **NOTE:** Be sure to maintain the power at a constant value of 5 W. Keep taking data until the temperature levels off to its new steady-state value (at least 15 min).

4. *Repeat the procedure* for the cooling of the power transistor. Switch off the power supply and start the stopwatch at the same time.

5. *Repeat the procedure* for the heating of the power transistor for a lower power level, say 3 W.

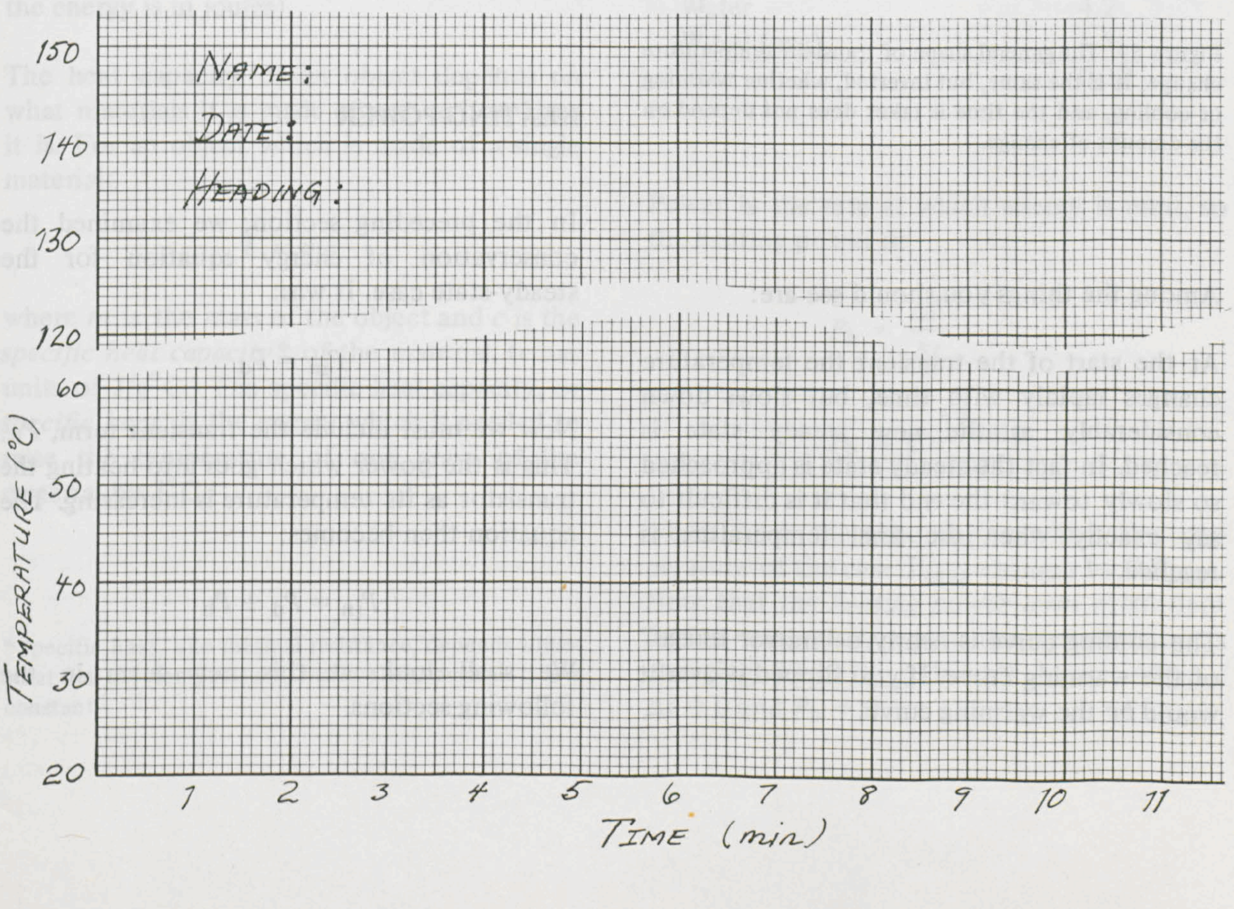
6. *Repeat steps 1, 2, and 3* with the transistor attached to the heat sink.

7. *Turn off all systems* when you have all of your data.

Graphing the Data

When the experiment is over, plot the data from steps 1 through 5 in a graph like the one below. Again, put all of your curves on the same sheet. Put the graphs for step 6 on a separate sheet.

The data for this experiment should be better than for the previous one. Because of this, it is worthwhile putting more time and care into making these graphs. Follow the same procedure as the last experiment with the following addition: Use a *French curve* to make a better than freehand curve through your data points. Ask your instructor for help if you don't know how to do this.



Qualitative Analysis of the Curves

You now have two sets of thermal transient data, one for the thermometer and one for the power transistor. Take a moment to compare the two sets with each other and with your predictions.

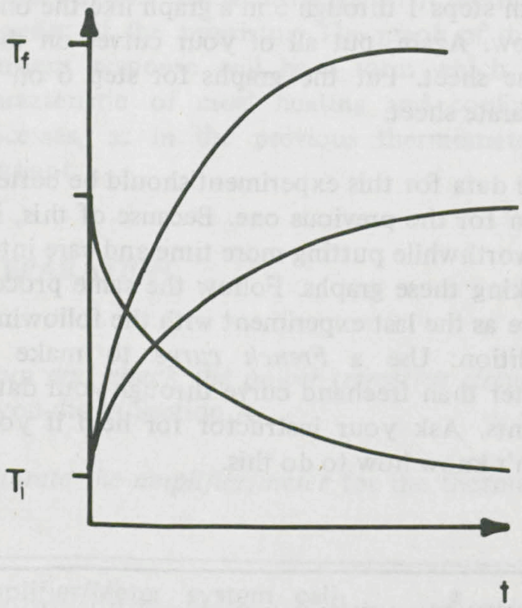


Figure 59. The general shape of transient temperature change. It is the same, but inverted, whether warming or cooling, and the time it takes does not depend on the amount of change.

Among the things you should see are:

At the start of the transient the temperature changes rapidly with time, but slows down considerably as the new steady state is reached. In fact the steady state is approached so slowly toward the end that it is difficult to say exactly when the final temperature is reached.

The cooling curve is nearly a "mirror image" of the warming curve. If you flipped it over it would *be* the warming curve.

The time for the transient is difficult to determine since it approaches the final state so slowly. However, it is about the same for warming as for cooling, and it is the same no matter how high the final temperature goes. See Figure 59.

Why a Quantitative Analysis Is Needed

This type of analysis is called *qualitative* since no numbers, or quantities, have been calculated from your data. But there *are* quantities that we would like to know. One, of course, is the time needed for the transient to take place. As you have seen, it is difficult to assign a time to when the curve reaches the final temperature since it approaches so slowly. Is there a way in which a time can be associated with such curves?

To describe the transients we need a quantitative analysis of the transistor behavior. Such an analysis is given in the following pages. The discussion is mathematical and is based primarily on the *Law of Conservation of Energy.*

HEATING POWER

In the preceding section, we examined the conservation of energy equation for the steady-state case. It was:

$$P_{in} = P_d$$

Now we must include the transient term, P_h. This is the power which goes into heating the transistor as its temperature is increasing. The equation then becomes:

$$P_{in} = P_d + P_h$$

We shall look at this new term in the following sections.

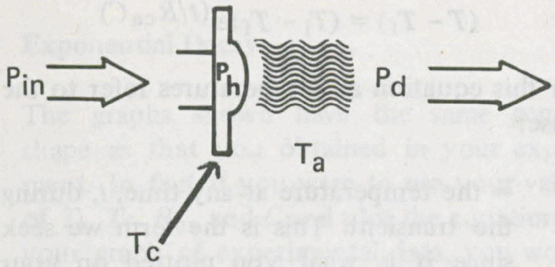


Figure 60. The electrical power input to the transistor is split between heating the transistor case and dissipating to the air.

Any thermal energy which is not lost to the surroundings acts to raise the temperature of the transistor. Thus, as it gets hotter, the transistor stores thermal energy.

The change in thermal energy of the transistor, ΔE, is a constant times the change in temperature, ΔT:

$$\Delta E = C\Delta T$$

The constant C is called the *heat capacity* of the object and it has the units of J/°C (when the energy is in joules).

The heat capacity of an object depends on what materials it is made of and on how large it is. For an object which is made of a single material:

$$C = mc$$

where m is the mass of the object and c is the *specific heat capacity** of the material. (c has units of J/g°C.) The specific heat capacity, or *specific heat,* is the energy which is needed to raise the temperature of one gram of the material by 1°C.

*Specific heat, like thermal resistance, depends somewhat on the temperature, but we will assume it is a constant.

For example, the power transistor is made primarily of aluminum, which has a specific heat of .88 J/g°C. (See Table V.) Its mass, plus that of the socket, is about 10 g, so it has a heat capacity of about 8.8 J/°C.

Table V.
Specific Heats of Some Common Substances

Substances	$c\left(\frac{\text{J}}{\text{g°C}}\right)$ @ 20°C
Aluminum	0.88
Brass (60%Cu,40%Zn)	0.39
Copper	0.39
Earth (dry clay)	0.92
Glass (approximately)	0.5–0.9
Gold	0.13
Ice	2.1
Iron (steel)	0.46
Lead	0.13
Mercury	0.14
Silver	0.23
Stone (granite)	0.80
Water	4.2
Wood (avg)	1.8
Zinc	0.39

Power is the rate at which energy is used, so the heating power is:

$$P_h = \frac{\Delta E}{\Delta t}$$

$$P_h = C\frac{\Delta T_{case}}{\Delta t}$$

where Δt is the time during which the temperature of the case T_{case} changes by ΔT_{case}. Note that the *heating power term exists only during transients,* when the temperature is changing. When T_{case} doesn't change, $\Delta T_{case}/\Delta t = 0$ and $P_h = 0$.

TRANSIENT TEMPERATURE BEHAVIOR

In determining the thermal resistance and case temperature for any power input, we looked at the steady-state condition (when the temperature was not changing). Mathematically, that meant that we could drop the $\Delta T/\Delta t$ term from the conservation of energy equation.

The reason for this section of the module, however, is to gain an understanding of the transient condition when the temperature *does* change. Mathematically, that is a much more difficult problem than the steady-state case. The complication is caused by the $\Delta T/\Delta t$ term, which represents the changing temperature.

TRANSIENT COOLING

It is easier to consider first the nature of transient cooling. To observe this, one starts with a hot transistor to which no electrical power is supplied ($VI = 0$). The thermal energy stored in the transistor is dissipated into the air as heat (power from hot transistor = dissipated power), and the conservation of energy equation becomes:

$$-C\frac{\Delta T_c}{\Delta t} = \frac{(T_c - T_a)}{R_{ca}}$$

The minus sign on the left denotes a *decrease* in transistor thermal energy, and T_c is the *average* case temperature during time Δt. Does this equation describe the behavior you observed? To answer this question, we must solve the equation for T_c. The method of solution is mathematically complicated. More important, however, is understanding what the solution is and what information it can provide.

The solution of this equation for the *case temperature in transient cooling* is:

$$(T - T_f) = (T_i - T_f)e^{-(t/R_{ca}C)}$$

In this equation all temperatures refer to the case:

T = the temperature at any time, t, during the transient. This is the term we seek since it is what you plotted on your graph.

T_i = the transistor's temperature when the power was turned off, $t = 0$.

T_f = its final temperature (T_{air}) when the transient is over.

e ≈ 2.718

The quantity "e" is a constant, which occurs often in mathematical analysis of physical problems. It is the base of a set of logarithms called "natural" logarithms (10 is the base of "common" logarithms), and it often appears raised to some power, as it is here. The quantity e^x is called the *exponential* of x, and it is often written as "exp(x)." We shall further examine the properties of exponentials.

The preceding equation can be more easily understood if we note that it has the same general structure as:

$$A = A_o e^{-x}$$

where: $A = (T - T_f)$

$$A_o = (T_i - T_f)$$

$$x = \frac{t}{R_{ca}C}$$

The exponential equation is an important one for physics since it describes the behavior of many physical phenomena. It is called an equation of *exponential decay*. (In this usage, "decay" means "decrease.") The behavior is graphed in Figure 61. The expression for the transistor cooling is graphed for comparison.

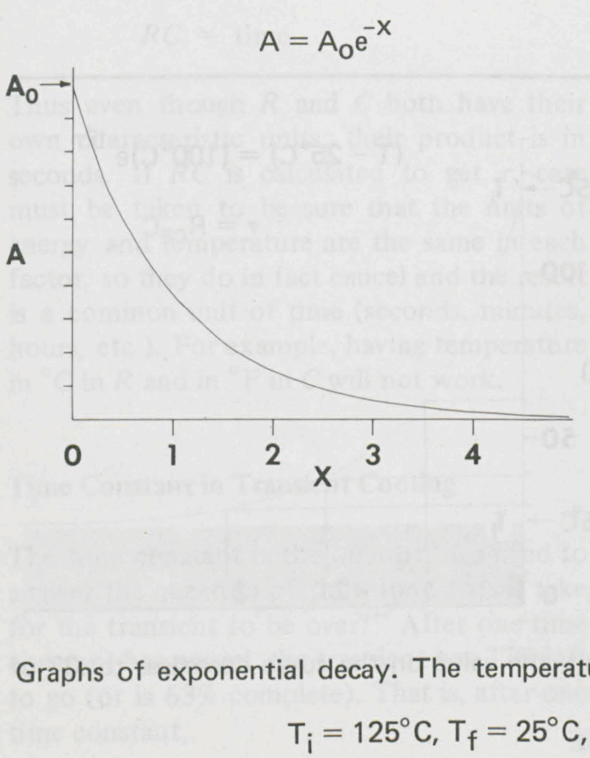
Exponential Decay

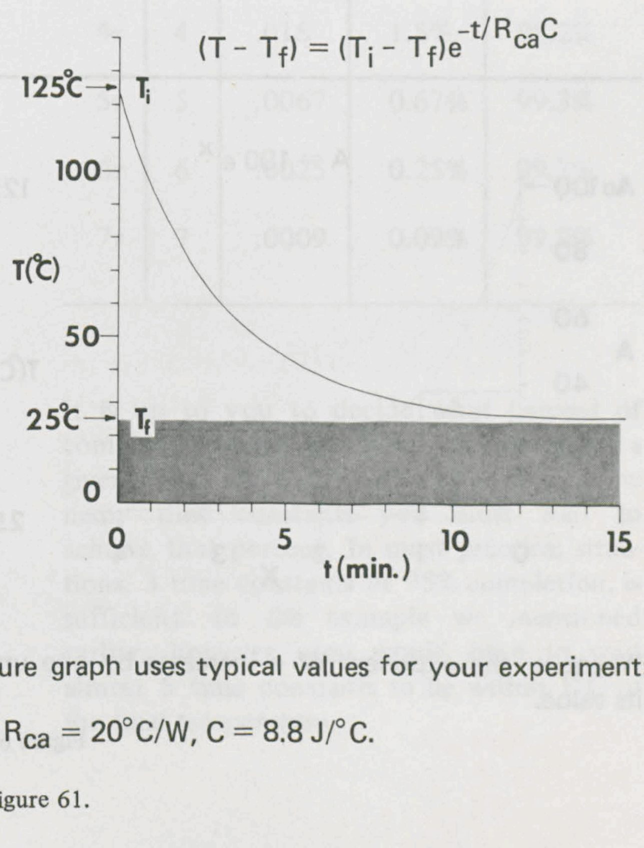
The graphs shown have the same general shape as that you obtained in your experiment. In fact if you were to use your values of T_i, T_f, R_{ca} and C and plot the equation on your graph of experimental data, you would find that it fits your curve very closely. (See Problem 5.) Thus our *mathematical* analysis is able to accurately describe what you observed *experimentally*. Since it describes the physical situation so well it is important to understand what the terms in the equation mean.

The first thing to note is that it is the *temperature difference* $(T - T_f)$ which is decaying (decreasing). In the illustration above, that difference was initially $(125°C - 25°C) = 100°C$. That is, the case was 100°C hotter than the air at the start. Over a period of time the temperature difference $(T - T_f)$ *decayed* to zero as T approached T_f.

The form of that decay was determined by the exponential term, $e^{-t/R_{ca}C}$ – thus the name *exponential decay*. Note that $(T - T_f)$ becomes zero very slowly; that is T approaches T_f very slowly. In fact the term e^{-x} always has a value greater than zero, being zero only when $x = \infty$. That means that the final temperature is reached only when $t = \infty$, an infinite time after the transient started.

This presents a problem. How can you assign a time for that transient when it is *never* over? (In the real world the temperature of the transistor soon gets so close to the temperature of the air that you can't measure a difference. But, mathematically speaking, one must worry about infinite times.)





Graphs of exponential decay. The temperature graph uses typical values for your experiment:

$T_i = 125°C$, $T_f = 25°C$, $R_{ca} = 20°C/W$, $C = 8.8\ J/°C$.

Figure 61.

The Time Constant

The mathematical relation says that the final steady-state is reached only at $t = \infty$. But for all practical purposes when the case temperature is less than 1°C above the air temperature, the transient is over. Therefore we *could* say that the time of the transient is from the time it starts to the time it reaches 1°C above the final temperature.

The nature of the exponential e^{-x}, however, lends itself to another, more meaningful measure. Whenever x increases by one unit, the value of e^{-x} decreases to .37, or 37%, of what is previously was. For example as x goes from 0 to 1, e^{-x} goes from $e^0 = 1$ to $e^{-1} = .37$. As x goes from 1 to 2, e^{-x} goes from .37 to $e^{-2} = .14$, which is $.37 \times .37 = .14$. And so on. When x in e^{-x} increases by 1, e^{-x} decreases to .37 of what it was. This is true no matter what the value of x.

Figure 62 shows this graphically for the expression $A = A_o e^{-x}$ where we have let $A_o = 100$ for simplicity. Choose two values for x and, using the graph, verify for yourself that the last statement is correct. Try some values which are not whole numbers.

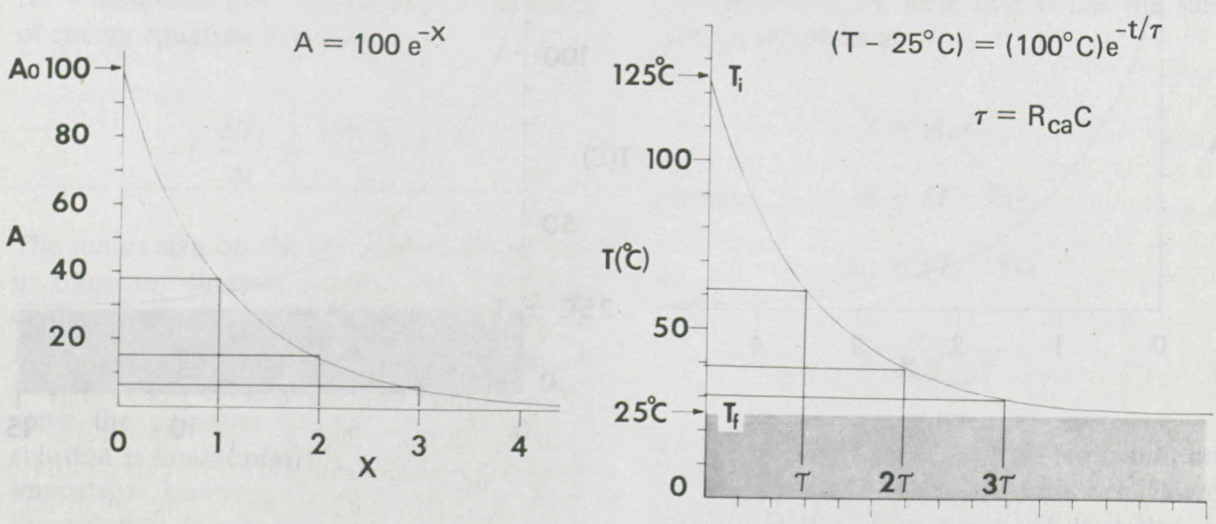
How do we relate this characteristic of the exponential to our temperature expression? In our expression, x is replaced by $t/R_{ca}C$. Thus when $t/R_{ca}C$ increases by 1, the temperature difference $(T - T_f)$ will decrease to .37 of what it previously was.

A simpler way to think of this is to define the Greek letter *tau* as:

$$\tau = R_{ca}C$$

Then the exponential term becomes $e^{-t/\tau}$. Then every time t increases by τ, say from $t = 2\tau$ to $t = 3\tau$, t/τ increases by 1 unit.

τ has units of time, since t/τ must be a "pure" number. (Exponents never have any units associated with them.) τ is commonly called the *time constant* of the process. In this case it is equal to the product of the thermal resistance and the heat capacity.



Whenever the exponent of e increases by one unit, the value on the curve decreases to .37 of its value.

Figure 62.

Why $R_{ca}C$ Represents a Time

You might ask how the product of thermal resistance and heat capacity can be equal to a time. The answer lies in an analysis of their dimensions (*dimensional analysis*), or the units that make them up. For example heat capacity C is expressed in J/°C. In dimensional words this is expressed as energy divided by temperature. The thermal resistance R is in °C/W or temperature divided by power. The dimensions of the product RC are therefore:

$$RC = \frac{\text{energy}}{\cancel{\text{temperature}}} \times \frac{\cancel{\text{temperature}}}{\text{power}}$$

or:

$$RC = \frac{\text{energy}}{\text{power}}$$

But since power is energy per time:

$$RC = \cancel{\text{energy}} \times \frac{\text{time}}{\cancel{\text{energy}}}$$

$$RC = \text{time}$$

Thus even though R and C both have their own characteristic units, their product is in seconds. If RC is calculated to get τ, care must be taken to be sure that the units of energy and temperature are the same in each factor, so they do in fact cancel and the result is a common unit of time (seconds, minutes, hours, etc.). For example, having temperature in °C in R and in °F in C will not work.

Time Constant in Transient Cooling

The time constant is the quantity we need to answer the question of "how long does it take for the transient to be over?" After one time constant has passed, the transient has 37% left to go (or is 63% complete). That is, after one time constant,

$$(T - T_f) = .37(T_i - T_f)$$

After 2 time constants it has 14% to go (86% complete). After 3 time constants it is 95% complete, and so on (see Table VI).

Table VI.

Relation of Elapsed Time to Percentage of Transient Cooling

t	t/τ	$e^{-(t/\tau)}$	percent to go	percent complete
0	0	1.00	100%	0
τ	1	.368	36.8%	63.2%
2τ	2	.135	13.5%	86.5%
3τ	3	.050	5.0%	95.0%
4τ	4	.018	1.8%	98.2%
5τ	5	.0067	0.67%	99.3%
6τ	6	.0025	0.25%	99.7%
7τ	7	.0009	0.09%	99.9%

It is up to you to decide what percent of completion of the transient you require for a given situation. Then you just look up how many time constants you must wait to achieve that percent. In most practical situations, 3 time constants or 95% completion, is sufficient. In the example we mentioned earlier, however, you would have to wait almost 5 time constants to be within 1°C of the final temperature.

HOW TO DETERMINE THE TIME CONSTANT

There are several ways to find the time constant for a transient process. We shall describe a few of these methods. They vary from a theoretical calculation, to an approximate graphical estimate, to a detailed analysis from the data. In a practical situation you must select the method which gives you the answer with the accuracy you need.

Theoretical Calculation

According to our theoretical treatment of transient cooling, we found that the time constant was given by:

$$\tau = R_{ca}C$$

You learned to determine the thermal resistance from your data in Section B. We estimated the value of the heat capacity of the transistor to be 8.8 J/°C. Using $R_{ca} = 20°\text{C/W}$, the time constant is:

$$\tau = \frac{20°\text{C}}{\text{W}} \times 8.8 \frac{\text{J}}{°\text{C}}$$

$$\tau = 176 \text{ s}$$

$$\tau \approx 3 \text{ min}$$

1. *Calculate the time constant* for *your* transistor alone by using your experimental value of R_{ca} and the estimated heat capacity. Use the methods of Section B to determine a value for R_{ca} and assume that the heat capacity of the transistor is 8.8 J/°C. If you are using a transistor different from the 2N3055 you will have to determine your own value for *C*.

2. *Record your values* on the data page.

Graphical Approximation

A graphical method for finding the time constant is to draw a *tangent* to the cooling curve at $t = 0$ and extend it to the value of the final temperature. It can be shown mathematically that the value of t where this line crosses T_f is the value of τ. The method is *only approximate* since it is difficult to draw the actual tangent at this point. See the figure.

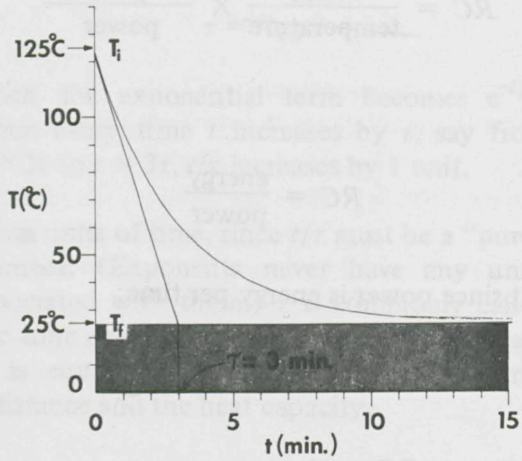


Figure 63.

3. *Determine the value of τ from your cooling curves* for the thermometer and the transistor by using this method, as shown in Figure 60.

4. *Record your value* in the data table.

Graphical Calculation (Method I)

A more precise method for determining the time constant from your graph is to use the fact that, after one time constant, the temperature difference $(T - T_f)$ is .37 of its initial value. The procedure is the following, and it is illustrated in the figure.

Find (T_i - T_f):

$$125° - 25°) = 100°C$$

Multiply by .37:

$$.37 \times 100° = 37°C$$

Add to T_f:

$$25°C + 37° = 62°C$$

Find the time associated with this temperature on the graph. It is the time constant τ.

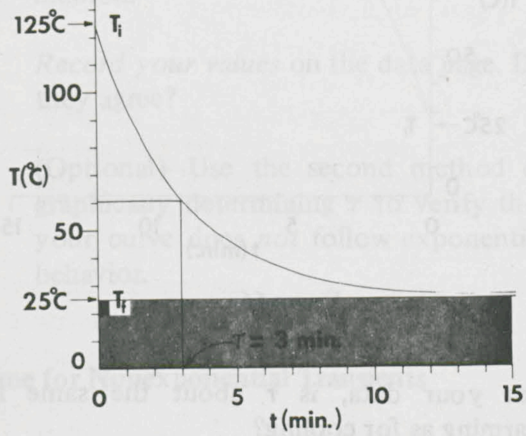


Figure 64.

5. *Determine the value of τ from your cooling curves* for both the thermometer and the transistor using this method.

6. *Record your value* in the data table.

Graphical Calculation (Method II–Optional)

A characteristic of exponential curves is that the slope (rise/run) of the exponential at any time t is related to the temperature difference at that point by:

$$\tau = -\frac{(T - T_f)}{\text{slope}}$$

In Figure 62, the temperature difference at $t = 6$ min is $(T - T_f) = (38.5° - 25°) = 13.5°C$. The slope at that point is $-4.5°C/\text{min}$ so that the time constant is:

$$\tau = \frac{13.5°C}{-4.5°C/\text{min}}$$

$$\approx 3 \text{ min}$$

If the curve is a true exponential you will get this value no matter where you draw the slope. Therefore, an approximate method for determining whether the curve is an exponential is to calculate τ by this method for a number of points along the curve. If they all give the same result then the curve follows exponential decay.

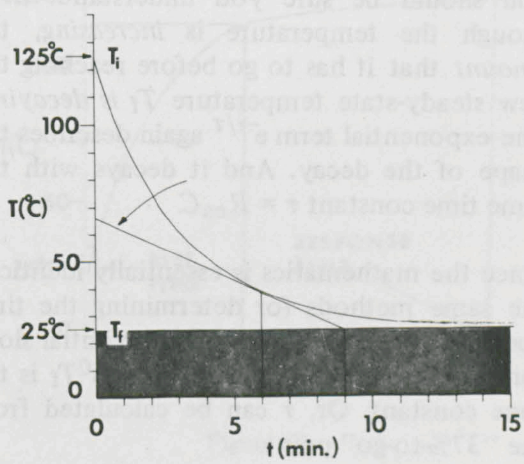


Figure 65.

7. *Verify that your curve is an exponential.* Calculate τ at a number of points and compare the values.

TRANSIENT WARMING

In the earlier qualitative analysis of your curves, you saw that the warming curve is a mirror image of the cooling curve. See Figure 63. Practically everything that has been said about transient cooling applies also to transient warming. The conservation of energy equation can again be solved to give a mathematical expression that fits your data.

The solution that describes *transient warming* is:

$$(T_f - T) = (T_f - T_i)e^{-(t/R_{ca}C)}$$

As you might expect, this expression looks quite similar to the previous one for transient cooling. The only difference is the reversal of T_f in the parentheses. This is because T_f is a higher temperature than T_i. But the *temperature difference* $(T_f - T_i)$ *still follows exponential decay (decrease).*

This is a very important point and one that you should be sure you understand. Even though the temperature is *increasing*, the *amount* that it has to go before reaching the new steady-state temperature T_f *is decaying.* The exponential term $e^{-t/\tau}$ again describes the shape of the decay. And it decays with the same time constant $\tau = R_{ca}C$.

Since the mathematics is essentially identical, the same methods for determining the time constant can be used. That is, the initial slope can be drawn and where it crosses T_f is the time constant. Or, τ can be calculated from the "37%-to-go" point.

7. *Determine τ for your warming curves* for the thermometer and for the transistor alone. Use both the graphical approximation and graphical calculation methods.

8. *Record your values* in the data table.

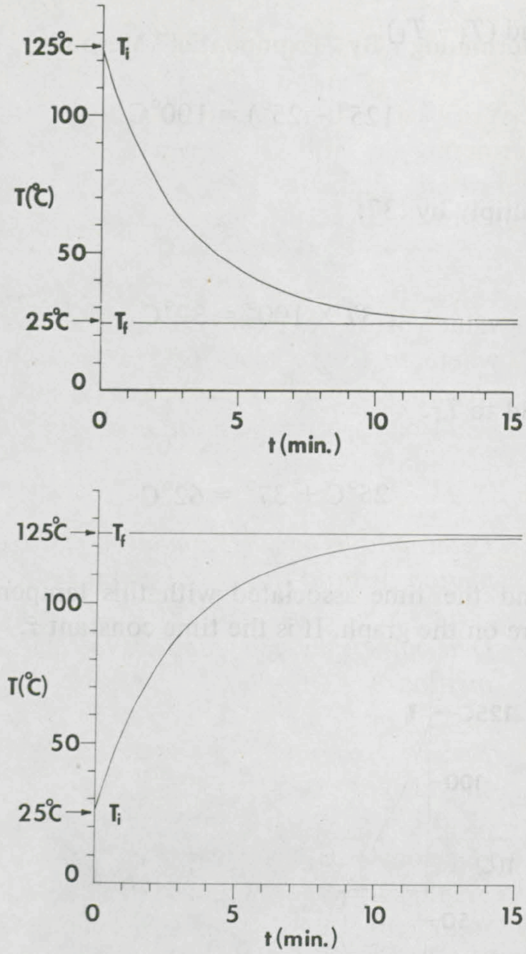


Figure 66.

For your data, is τ about the same for warming as for cooling?

NONEXPONENTIAL TRANSIENTS

Now what about the transient temperature data you took for the heating of the transistor plus heat sink? In comparing the shape of this curve to those of the heating of the transistor alone, it is clear that the temperature difference did not decay by a simple exponential. Instead, there was a much more uniform approach to the final steady-state temperature.

Determining τ By "Exponential" Methods

To verify that our previous methods for determining τ will *not* work for *non-exponential* transients apply them to your graph. For the transistor plus heat sink:

1. *Calculate* $\tau = R_{ca}C$ from your measured value of R_{ca}. First calculate $C = mc$ where m is the mass of the transistor *plus* the heat sink. Since the heat sink is also made of aluminum you can use $c = .88 \text{J/g}^\circ\text{C}$.

2. *Determine* τ *by the graphical approximation method* from your graph.

3. *Determine* τ *by the graphical calculation method.*

4. *Record your values* on the data page. Do they agree?

5. (Optional)–Use the second method of graphically determining τ to verify that your curve does *not* follow exponential behavior.

Time for Nonexponential Transients

Your values of τ probably did not agree very well. For nonexponential transients the mathematical treatment of Section C no longer applies, and other methods for measuring the time for the transient are used.

One way is to simply measure the *total time* it takes to go between the two steady states. This time is usually called the *response time* for the transient.

Another way is to measure the time it takes to go from 10% complete to 90% complete. The procedure is the following and is shown in Figure 67.

Find $(T_f - T_c)$:

$$(125^\circ - 25^\circ) = 100^\circ\text{C}$$

Multiply by .10:

$$.10 \times 100 = 10^\circ\text{C}$$

Add to T_c:

$$25^\circ + 10^\circ = 35^\circ\text{C}$$

Subtract from T_f:

$$125^\circ - 10^\circ = 115^\circ\text{C}$$

Find the times associated with 35° and 115°.

The difference in these times is called the *rise time* for the transient. For decreasing transients it is called the *decay* or *fall time.*

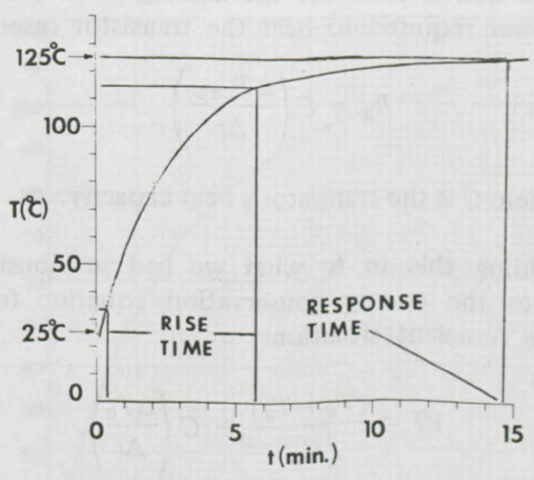


Figure 67.

6. *Determine the response time and the rise time* from your graph. Record your values.

As can be seen from your results these methods are only qualitative.

REVIEW

Summary

A *transient* is a change that takes place in a relatively short time between two steady states. A *steady state* is one in which there is no significant change in some characteristic of a system as time passes. The experiments of this section showed that, for simple thermal situations, transients in temperature take place in a way described by *exponentials. Transient decay* and *transient growth* are "mirror images" of each other. The exponential form of the curves is the same.

Conservation of energy states the fact that energy changes form but doesn't disappear. In Section B, an equation was developed for the conservation of energy for the steady-state. When transients are involved, we must also add a term for the *heating power*, the power required to heat the transistor case:

$$P_h = C\left(\frac{\Delta T_{case}}{\Delta t}\right)$$

where C is the transistor's heat capacity.

Adding this in to what we had previously gives the energy conservation equation for the transient situation:

$$VI = \frac{(T_c - T_a)}{R} + C\left(\frac{\Delta T_c}{\Delta t}\right)$$

This equation can be solved mathematically to give the *time constant* for thermal change:

$$\tau = RC$$

τ is equal to the time at which the *temperature difference* is equal to 37% of its original value. The time constant is the same for both transient decay and transient growth, and it is a measure of how long it takes for thermal transient to take place.

Another result of the experiments was to show that not all heating and cooling follows exponential decay. Such terms as *response time, rise time* and *decay time* are used to indicate how long transients take for these systems.

Questions

1. a. Why does a mercury thermometer respond so much more slowly in air than it does in water?

   b. If the thermal resistance between the mercury thermometer and its surroundings could be made equal to zero, the thermometer would still take time to respond. Why is this? Is the same thing true of a thermocouple? Why or why not?

2. a. What would be the equation for conservation of energy if the power transistor were put in a closed box that didn't let any heat flow out of it?

   b. In this case, what would happen to the temperature of the transistor if a constant electrical power was put into it?

   c. If the power is turned off, what is the conservation equation? What happens to the temperature?

   d. What would you use for an "insulating box" such as the one described in 2a? (There aren't any perfect ones. Why not?)

3. Is there a thermal resistance when a mercury thermometer is used to measure water temperature, just as there is in measuring transistor temperature? If there is, why is the mercury thermometer more accurate for measuring the temperature of water than it is for the transistor?

Problems

1. A beaker of 750 g of water is heated on a burner which supplies an input power of 1000 W. How long will it take to get the water to the boiling point (100°C) if it starts at 20°C?

   In this calculation, neglect heat losses to the surroundings. If these were included, would your answer be greater or smaller? Why?

2. A cup of coffee (about 500 g, with a specific heat about the same as water) took half an hour to cool to nearly room temperature.

   a. Estimate the time constant for this process.

   b. Using this, determine the thermal resistance between the coffee and its surroundings. (Assume that it starts out boiling hot.)

3. A transistor is supplied with an input power of 3 W, and the thermal resistance from the case to the air is 5°C/W. How hot will the transistor get when it is in a room at 30°C?

4. a. Given the transistor heating graph in Figure 68, find the time constant in two ways. The power input is 5 W.

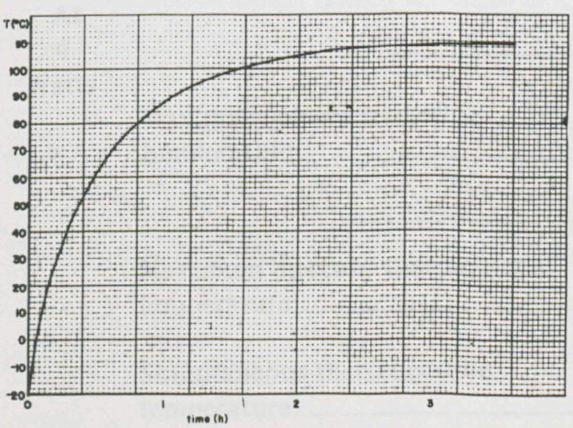


Figure 68

   b. Draw the graph of what would happen if the power were suddenly turned off, starting with $T = 110$°C. Let $t = 0$ be the time it was turned off.

   c. What is the thermal resistance for the situation for which the graph was made?

   d. What is the heat capacity of the transistor?

   e. What is the mass of the transistor if it is made of aluminum?

   f. What would T_f be if $P = 7$ W?

5. Is the curve of Figure 69 an exponential? How can you tell? What is the *response time* if this graph was the heating curve for a system which was heated with a constant power input? What is the *rise time*?

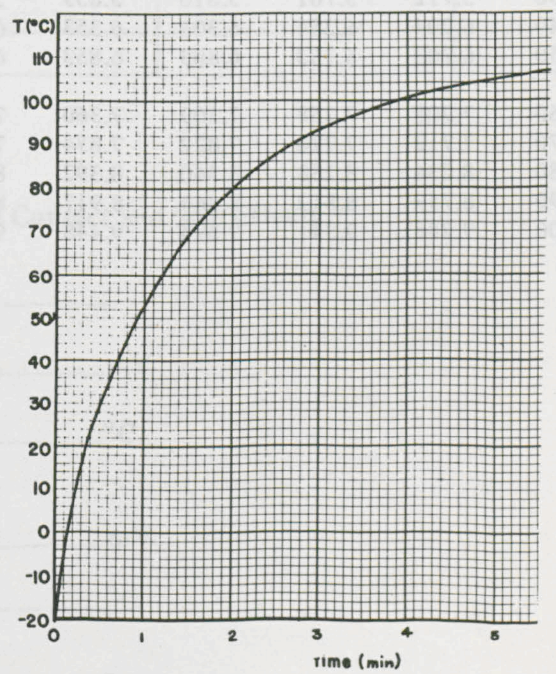


Figure 69

APPENDIX

CALIBRATION TABLE

COPPER-CONSTANTAN THERMOCOUPLE

REFERENCE JUNCTION 0°C

°C	0	1	2	3	4	4	6	7	8	9
					millivolts					
(+)0	0.000	0.038	0.077	0.116	0.154	0.193	0.232	0.271	0.311	0.350
10	0.389	0.429	0.468	0.508	0.547	0.587	0.627	0.667	0.707	0.747
20	0.787	0.827	0.868	0.908	0.949	0.990	1.030	1.071	1.112	1.153
30	1.194	1.235	1.277	1.318	1.360	1.401	1.443	1.485	1.526	1.568
40	1.610	1.652	1.694	1.737	1.779	1.821	1.864	1.907	1.949	1.992
50	2.035	2.078	2.121	2.164	2.207	2.250	2.293	2.336	2.380	2.423
60	2.467	2.511	2.555	2.599	2.643	2.687	2.731	2.775	2.820	2.864
70	2.908	2.953	2.997	3.042	3.087	3.132	3.177	3.222	3.267	3.312
80	3.357	3.402	3.448	3.493	3.539	3.584	3.630	3.676	3.722	3.767
90	3.813	3.859	3.906	3.952	3.998	4.044	4.091	4.138	4.184	4.230
100	4.277	4.324	4.371	4.418	4.465	4.512	4.559	4.606	4.654	4.701
110	4.749	4.796	4.843	4.891	4.939	4.987	5.035	5.083	5.131	5.179
120	5.227	5.275	5.323	5.372	5.420	5.469	5.518	5.566	5.615	5.663
130	5.712	5.761	5.810	5.859	5.908	5.957	6.007	6.056	6.105	6.155
140	6.204	6.254	6.303	6.353	6.403	6.453	6.503	6.553	6.603	6.653
150	6.703	6.753	6.803	6.853	6.904	6.954	7.004	7.055	7.106	7.157
160	7.208	7.258	7.309	7.360	7.411	7.462	7.513	7.565	7.616	7.667
170	7.719	7.770	7.822	7.874	7.926	7.978	8.029	8.080	8.132	8.184
180	8.236	8.288	8.340	8.392	8.445	8.497	8.549	8.601	8.654	8.707
190	8.759	8.812	8.864	8.917	8.970	9.023	9.076	9.129	9.182	9.235
200	9.288	9.341	9.394	9.448	9.501	9.555	9.608	9.662	9.715	9.769

DATA PAGES – SECTION A

EXPERIMENT A-3. Comparing the Thermocouple and the Mercury-in-Glass Thermometer

THERMOMETER	*RANGE*	*SENSITIVITY*	*ACCURACY*	
			0°C	*100°C*
Mercury-in-glass	°C	± °C	°C	°C
Thermocouple	mV °C	± mV ± °C	mV °C	mV °C

THERMOMETER		*RESPONSE TIME*		
		cold water	*hot water*	*air*
Mercury-in-glass	1			
	2			
	3			
	avg			
Thermocouple	1			
	2			
	3			
	avg			

EXPERIMENT A-4. Thermal Contact and Size Effects

Response time of power transistor: ____________________

Maximum touch temperature: ____________________ mV

At 4 Watts

____________________ °C

Maximum power transistor temperature: ______________________________ mV

______________________________ °C

Maximum mercury thermometer temperature: ______________________________ °C

Simultaneous thermocouple temperature: ______________________________ mV

______________________________ °C

COMPUTATION SHEET

DATA PAGES – SECTION B

EXPERIMENT B-1. Heat Transfer in the Transistor

Room Temperature: $T_a =$ °C

$VI = 3$ W	$VI = 5$ W
$T_f =$ °C	$T_f =$
$R_{ca} =$	$R_{ca} =$

EXPERIMENT B-2. Adding a Fan

$VI = 12$ W	$VI =$	$VI =$	$VI =$
$T_f =$	$T_f =$	$T_f =$	$T_f =$
$R_{ca} =$	$R_{ca} =$	$R_{ca} =$	$R_{ca} =$

EXPERIMENT B-3. Adding a Heat Sink

$VI = 30$ W	$T_{\text{heat sink}} =$
$T_f =$	$R_{cs} =$
$R_{ca} =$	

EXPERIMENT B-4. Using Both a Heat Sink and Fan

$VI = 30$ W	$VI =$	$VI =$	$VI =$
$T_f =$	$T_f =$	$T_f =$	$T_f =$
$R_{ca} =$	$R_{ca} =$	$R_{ca} =$	$R_{ca} =$

COMPUTATION SHEET

DATA PAGES – SECTION C

EXPERIMENT C-1. Transients in a Mercury Thermometer

(Make table here)

$T_{air} =$

EXPERIMENT C-2. Transients in a Transistor

(Make table here)

Exponential Transients

	COOLING	*WARMING*
Calculation: $\tau = R_{ca}C$		
GRAPHICAL APPROXIMATION:		
Thermometer–		hot warm
Transistor–		5 W 3 W
GRAPHICAL CALCULATION:		
Thermometer–		hot warm
Transistor–		5 W 3 W

Determination of Heating Time Constant for Transistor and Heat Sink

1. Calculation: $\tau = R_{ca}C =$
2. Graphical approximation $\tau =$
3. Graphical calculation $\tau =$
6. Response time =

   Rise time =

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